Full citation: Tilley, David Rogers. "National Metabolism and Communications Technology Development in the United States, 1790–2000." *Environment and History* 12, no. 2 (May 2006): 165–90. http://www.environmentandsociety.org/node/3263.

National Metabolism and Communications Technology Development in the United States, 1790–2000

DAVID ROGERS TILLEY

Biological Resources Engineering
College of Agriculture and Natural Resources
Building #142, Room 1449
University of Maryland
College Park, MD 20742, USA
Email: dtilley@umd.edu

ABSTRACT

The accelerating rate of technology development during the past two centuries was coupled to a hastened pace of national metabolism, which included vast consumption of fossil fuels, mineral deposits, virgin timber, rich soils and other natural resources, and the construction of an international medium for the communication and storage of ideas and discoveries. The development, maintenance, and improvement of technology, defined anthropologically as physical devices and mental knowledge of how to employ such devices, requires energy. New technologies provide powerful and flexible means for organising subsequent system structure and function, and nourish opportunity for more discovery and technical innovation. From a systems ecology perspective, technology development is an evolutionary process, which implies that it is a self-organising, autocatalytic process driven by energy and resource availability, population size, economic development, scientific knowledge and previous innovation. Understanding how the dynamics of technology development were related to historical resource use (i.e., national metabolism) is important in a world operating mostly on finite resources because it can offer some perspective on the effects of future resource limitations on technology development. Emergy (with an 'm') evaluation, a physically based environmental accounting system that tracks the total amount of resources required to produce something by tracing all resource flows back to the Earth's ultimate energy source of solar radiation, was employed to measure national metabolism of the United States during the past two centuries and to estimate the national metabolism required to develop and maintain the broad-use of four communication technologies. National metabolism of the US grew exponentially from 1790 to 2000, increasing 1600 per cent during those 210 years. The national metabolism required to develop and maintain use of satellites, radios, televisions and telephones approached a minimum, indicating

Environment and History **12** (2006): 165–90

that limits to efficiency improvements exist and that the ubiquity of large-scale technologies surviving under future resource limitations is doubtful.

KEY WORDS

U.S. energy use, fossil fuels, natural resources, emergy evaluation, technological innovation

1. INTRODUCTION

Technological optimists like Julian Simon claim technological innovation has no bounds, indicating that the economic importance of physical materials will diminish in the future as the prominence of information services grows.[1] Some suggest that the net consumption of natural resources could approach zero as humanity evolves into an information society. Others, like Amory Lovins, believe that society's energy limitations can be overcome through endless improvement in efficiency.[2] Certainly, the expansion of the World Wide Web has increased information processing in many developed countries, forming the basis of a few new modes of commerce (e.g., on-line auctions, web searching). Technological optimists point to the proportional increase in gross domestic product (GDP) that is attributed to the information services sectors, the explosive increase in digital-based business activity, and the decline in the proportion of US GDP derived from mining, agriculture and manufacturing as support for their thesis. 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, desktop computing and the satellite. But how well do we understand the total energy basis of technological innovation and maintenance?

Joseph Tainter, when arguing his case that societies collapse due to the diminishing marginal return of investing in more social and economic complexity, recognised that technical innovation required the dissipation of energy.[3] Tainter promoted Richard Wilkinson's assertion that technical innovation often occurred because society was responding to some environmental or economic distress, of which the example of England switching from wood to coal to set the stage for developing the steam engine, which eventually begat the Industrial Revolution, is an archetype.[4]

Both Tainter and Wilkinson agreed that technology development was an evolutionary process with current successes dependent upon previous achievements and future innovations dependent on current successes. Jared Diamond argued that the rate of technology improvement was closely tied to a culture's history, environment and geography, rather than to the work of particular geniuses.[5] In his view, the general theory of relativity, for which Albert Einstein received much praise, would eventually have been developed by someone else. Howard T. Odum related innovation directly to the availability of excess power to society, stating, 'The power cost of innovation is the power cost of making even more choices and selections than are required to hold the order stable'.[6] Conversely, power limitation may reduce innovation and force loss of previously developed technological knowledge.

Figure 1 provides an ecological systems context for placing the role of technical innovation with respect to open systems energy flow, material cycles, thermodynamic laws (conservation and entropy), and autocatalytic production of physical assets and technical knowledge. In the conceptual model, natural systems pull together the continuous flow of free energy (i.e., solar power) with abundant dispersed materials (e.g., carbon dioxide, nitrogen gas) to produce concentrated stocks of natural capital (e.g., wood, soil, petroleum). Natural capital forms the base of an economic production system that simultaneously builds physical capital (e.g., labour, manufacturing plants, machines, transportation infrastructure) and innovates technology (i.e., software, software engineers, accounting, accountants, textbooks, blueprints, instruction for how to build a motor, etc.) to produce a storage of shared knowledge capital. Positive feedback from physical and knowledge capital complete the autocatalytic loop that accelerates economic production and technological innovation which are parallel processes that consume natural capital. In this model, technological innovation is an integrated, autocatalytic process coupled to energy consumption and eco-

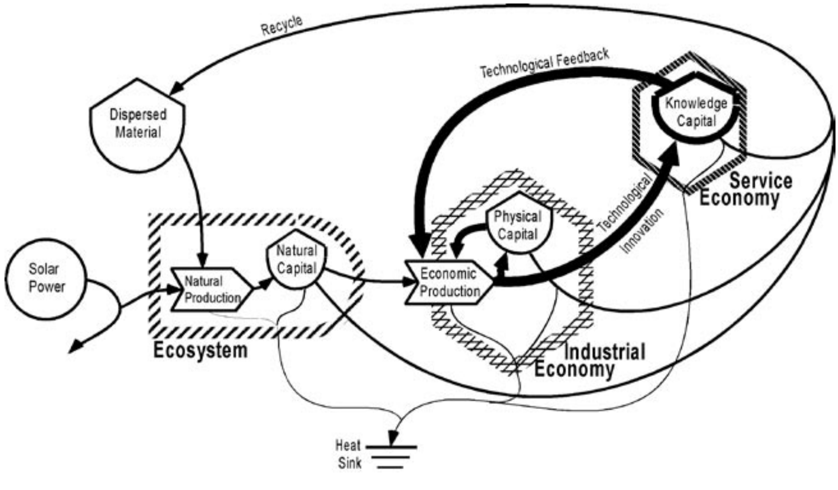


FIGURE 1. Systems ecology model of natural resource consumption for economic and technological development.

nomic production, that is battling the entropic characteristic of information that causes it to be lost, forgotten, degraded,and filled with errors.

During an early period when natural capital was abundant (e.g., beginning of age of coal), and physical and knowledge capital were relatively low, simulations of the model showed that growth of both forms of capital accelerated exponentially as did technological innovation.[7] (In the U.S., patent grants as an index of technology exhibited approximately this type of growth from 1790 to 2000, Figure 2). During the next phase (i.e., intermediate availability of natural capital and energy), economic production of physical and knowledge capital, and consumption of natural capital slows, but remains greater than depreciation losses of physical and knowledge capital. As natural capital availability shrinks and the amount of physical and knowledge capital becomes large, there comes a turning point when economic production cannot compensate for the burdening effort required to maintain second law depreciation losses occurring to physical and knowledge capital. Eventually, this leads to small amounts of physical and knowledge capital.

Tainter's diminishing returns theory of technological innovation is present in the model. The ratio of economic production to technology maintenance is analogous to Tainter's concept of marginal return (i.e., ratio of economic return to economic cost). The model supports Tainter's assertion that a peak in marginal return accompanies collapse, but stipulates that the peak occurs before the peak in gross economic production. In this regard, predictions of immediate economic and social descent following the global peak in crude oil production[8] are slightly premature because as a general phenomenon, net growth of an asset stock fuelled by a non-renewable resource (e.g., economic assets) continues

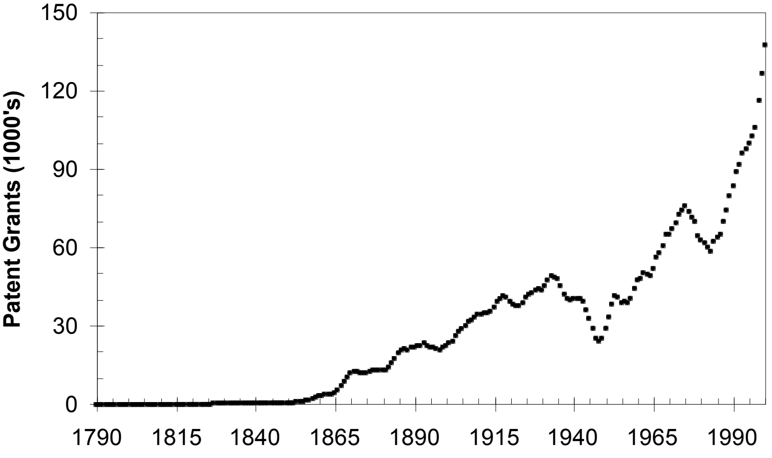


FIGURE 2. U.S. patent grants.

after peak production. This implies that even if petroleum were our only energy source and its production peaked in 2007, net growth of the economy would continue until 2020 or 2030.[9]

Therefore, given that there are questions about the relationship between technological innovation and its supporting base of energy and other natural resources, I set forth in this paper to estimate the level of resource and energy consumption used within the U.S. from 1790 to 2000 to achieve its rate of technological innovation. We used the environmental accounting technique known as solar emergy synthesis to integrate all of the various forms of resources used within the country (e.g., water, wood, soil, crude oil, hydroelectricity, non-fuel minerals) into a single unit of measure that we call national metabolism. Solar emergy is the total amount of solar energy required both directly and, most importantly, indirectly to make a product or provide a service.[10] Translation of all resource flows to solar emergy places them in a single unit called solar-embodied joules (sej). This form of unit transformation is critical when attempting to measure national metabolism because the various units of natural resources cannot be summed directly. Conversion to a single unit that is based on the total amount of the Earth's primary energy source not only allows for aggregation to estimate national metabolism, but it also automatically sets a global analytical boundary that ensures the inclusion of all necessary inputs.

As this paper will demonstrate, the energy consumed directly by communication devices, like telephones, is minor relative to the energy and natural resources consumed *indirectly* during the process of creating the technology and maintaining its infrastructure support. To compare the evolutionary progression in the total resource intensity of four of the most popular communication technologies (i.e., phone, television, radio, satellite), I evaluated the total solar emergy required per unit of energy used directly by each device over the period of its existence up to the year 2000. The ratio of solar emergy required to energy used was defined as the solar transformity by Odum.[11] For reference the solar transformity of solar radiation was defined as 1 sej per Joule (sej/J). In a world struggling with a decline in resource availability, understanding how much energy and natural resources are required for our global communication activities can inform the debate on the substitutability of information for physical goods. Since emergy accounting avoids some of the pitfalls of using monetary indices to estimate the wealth of past societies, and it provides a means to aggregate total resource consumption, environmental historians may find some utility in it for contrasting the total resource availability and energy use of historical societies.

In addition to estimating the solar emergy required to create and maintain communication technologies, the paper, as a necessary step towards that end, estimates a historical record of the various components of national metabolism, which offers data on, for example, the solar emergy derived from agriculture compared to fossil fuels and the pressure placed on the environment during economic growth. The dynamic relationship between gross economic product and national metabolism is reported for 1790–2000 period, which serves as an alternative measure of historical inflation. Per capita national metabolism is estimated for the same period and is offered as an alternative estimate of living standard; one that integrates the facets of various development stages of civilisations.

2. 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.[12] 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 3 presents an energy systems diagram that gives the philosophy for how national emergy was allocated to technological 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 4. 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 were mostly virgin sources that included solar emergy expended prior to 1790. A strong argument could be made that much of our latter-day domestic wood production (post-1920) is from secondary, regenerated forests, which consists of solar emergy from the post-1790 period. This is a detail that could be improved upon in subsequent historical emergy evaluations.

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

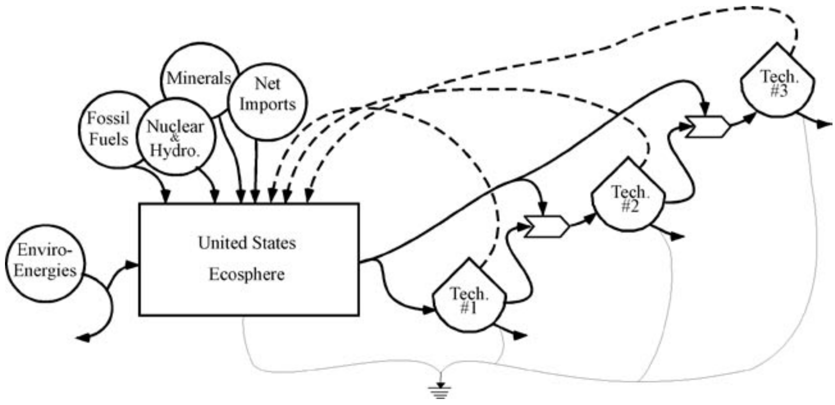
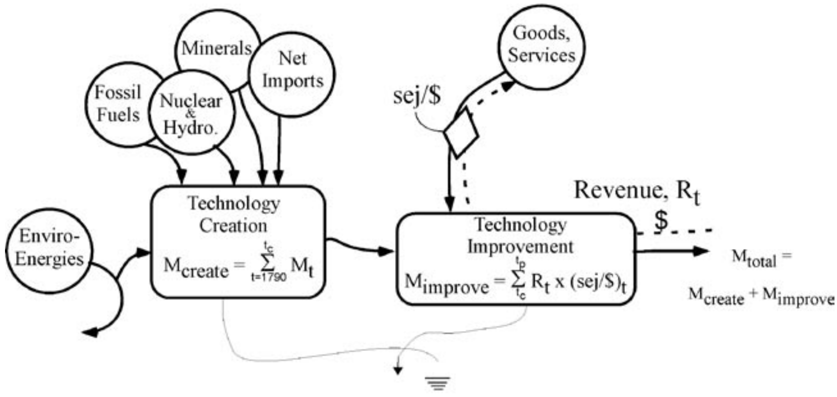


FIGURE 3. Systems diagram of U.S. technology development.



Where, M_{create} is solar emergy required to create a technology developed in creation year t_c;
M_t is annual national solar emergy use in year t;
$M_{improve}$ is solar emergy 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 emergy to dollar ratio for year t; and
M_{total} is total solar emergy accumulated in the technology.

FIGURE 4. Energy systems diagram with mathematical equations for estimating solar emergy to create and improve technologies.

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 (see below).

Equations for estimating solar emergy inputs

The methods and equations used to estimate the historical solar emergy use of the United States is presented below for each type of input.

Precipitation

The solar emergy of precipitation was found using Equation 1.

$$M_{pt} = L_t p_t S_r \tag{1}$$

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/yr based on visual interpolation of digital maps with colour-coded monthly precipitation rates.[13] The 1790 to 1803 precipitation rate was 1112 mm/yr. Changes to land area (L_t) were taken from Carter for the 1790–1970 period and from U.S. Census Bureau for post-1970.[14] The Gibb's free energy of freshwater precipitation was taken as 5 J/g-water. The solar transformity of precipitation was a constant 18,200 sej/J.

Soil Resources

The solar emergy of soil erosion in year t (M_{ot}) was found using Equation 2.

$$M_{ot} = F_t(5.68 \text{ tonne/acre})(0.03 \text{ g-org./g-soil})(22.6 \text{ kJ/g-org.})(63{,}400 \text{ sej/J}) \tag{2}$$

where F_t is farmland area in acres for year t (1 acre is approximately 4000m^2) and g.-org. is soil organic matter in grams.

F_t was given by Carter for the period 1900–1970 and by the U.S. Census Bureau for 1971–2000. For the 1850–1900 period, Carter only reported decadal records.[15] 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 acres per person). The 5.675 tonne erosion rate is a weighted average (by area) of cropland (7.5 tonne acre^{-1} yr^{-1}) and pasture (1.3 tonne acre^{-1} yr^{-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 Equation 3a.

$$M_{wt} = 544 \text{ MJ/ft}^3(W_t)(41{,}000 \text{ sej/J}) \tag{3a}$$

where W_t is wood consumption in cu.ft. (green weight); (1 ft^3 = 0.0283 m^3).

Total annual wood consumption was determined using Equation 3b.

$$W_t = W_p + W_f + W_i - W_e \tag{3b}$$

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; post-1970 W_t was given by Howard; pre-1900 lumber and total roundwood production were given on a decadal basis by Carter.[16] 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 W_f. 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) was taken from Tilley, which was based on simulated values of a 200-year-old forest.[17]

Immigration

The annual solar emergy of immigrants arriving in the U.S. (M_{it}) was estimated using Equation 4.

$$M_{it} = 0.1(\text{U.S. per cap. emergy use})(\text{average age})(\text{net immigration rate}) \qquad (4)$$

Equation 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 one-tenth 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 for the period 1820–1970. Lacking data on immigration prior to 1820 I assumed it to be zero. Post-1970 immigration was given by U.S. Census Bureau.[18]

Fuels and Electricity

Equations 5a, 5b, 5c, 5d, and 5e were used to calculate the annual solar emergy of crude petroleum (Mp_t), coal (Mc_t), natural gas (Mn_t), hydroelectricity (Mh_t), and nuclear electricity (Mu_t) 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.[19]

$$\text{Mpt} = 6.28\text{ E9 J/bbl x Pt x 54,000 sej/J} \qquad (5a)$$

$$\text{Mct} = 31.0\text{ E9 J/short ton x Ct x 39,000 sej/J} \qquad (5b)$$

$$\text{Mnt} = 1.10\text{ E6 J/cubic ft x Nt x 48,000 sej/J} \qquad (5c)$$

$$Mht = 3.606 \text{ J/kWh} \times Ht \times 160{,}000 \text{ sej/J} \quad (5d)$$

$$Mut = 3.606 \text{ J/kWh} \times Ut \times 160{,}000 \text{ sej/J} \quad (5e)$$

Non-fuel Minerals

The solar emergy consumed as non-fuel mineral *k* (M_{NFMk}) for the 1790–1970 period was estimated for minerals listed in Table 1 using Equation 6a.

$$M_{NFMk} = C_{nfmk} \times m_{nfmk} \quad (6a)$$

TABLE 1. Solar transformities of energy and mass specific solar emergy of materials used to convert energy and material flows to solar emergy.

Item	Data Source[20]	Solar Transformity (sej/J)	Mass Specific Solar Emergy (sej/g)
Rainfall	a	18,200	
Coal	a	39,000	
Fuel Wood	b	41,000	
Natural Gas	a	48,000	
Crude Petroleum	a	54,000	
Soil erosion (organic matter)	a	63,400	
Petroleum Products	a	66,000	
Electricity	a	160,000	
Fish	a	2,000,000	
Phosphate Rock	a		3.90E+09
Aluminium	c		3.42E+09
Chromium	c		4.07E+09
Copper	c		6.58E+10
Gold	c		1.32E+14
Iron	c		2.04E+09
Lead	c		1.24E+10
Manganese	c		1.07E+10
Molybdenum	c		7.13E+11
Nickel	c		5.43E+10
Silver	c		3.29E+11
Tungsten	c		1.53E+11
Uranium	c		5.70E+11
Vanadium	c		1.02E+11
Zinc	c		1.58E+10

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/g.

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 Equation 6b to estimate total non-fuel mineral consumption for the 1971–2000 (M_{NFM2}).

$$M_{NFM2} = (M_{Fe}+M_{Cu}+M_P)/0.78 \tag{6b}$$

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.

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/$). We used Equation 7a to calculate the M/$ for 1869–2000 period and Equation 7b for the 1790–1869 period.

$$M/\$_t = M_t/G_t \text{ for } 1869 < t < 2000 \tag{7a}$$

where M_t is total annual solar emergy use in year *t*; G_t is gross domestic product for *t*.

$$M/\$_t = 10^{(-0.0180t+48)} \text{ for } 1790 < t < 1868 \tag{7b}$$

Equation 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 Equation 7c.

$$M_{it} = M/\$_t * N_{it} \tag{7c}$$

where N_{it} is annual net imports in dollars for year *t*. Data for N_{it} were taken from US Census Bureau for the 1790–2000 period.[21]

Solar Transformities of 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 4) divided by the total power consumed by the total number of devices in operation. The critical variables for estimating M_{total} were t_c (creation year) and R_t (annual revenue of a technology's economic sector), 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 solar transformity to be overestimated in a technology's early history because the denominator is smaller than it should be. Better estimates of device power consumption could improve a subsequent analysis. Time series data on the number of devices in use came from the U.S. Census Bureau and Carter.[22]

TABLE 2. Critical variables for estimating M_{total} in Figure 4 and power consumption of devices.

Technology	t_c	Device Power	R_t
Satellite	1965	5.6 W per kg of payload	100% of U.S. GDP
Telephony	1870	1.0 W per set	Telephony sector estimated as 2.41% of GDP, which was the average share for period 1980–2000.
Radio	1922	10 W per set	Consumer spending for radio estimated as 0.02% of U.S. GDP, which was average rate from 1995–2000.
Television	1946	150 W per set	Consumer spending for TV estimated as 0.5% of U.S. GDP, which was average rate from 1995–2000.
Mail	n.a.	103 kJ per piece	U.S. Post Office revenue

3. RESULTS AND DISCUSSION

History of National Solar Emergy Use

Total solar emergy use in the U.S. grew at an exponential rate during the country's first 210 years of existence (Figure 5a). When the country was young, Thomas Jefferson's purchase of the Louisiana Territory from Napoleon in 1803 increased solar emergy availability to Americans by 36%. However, 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 1960s was the period of greatest absolute increase in solar emergy use, led by spending on the Vietnam War, with an average increase in the rate of growth of 14.7 E22 sej (3.4% per annum; E22 means x 10^{22}).

Within the general trend of increased solar emergy use there were important periods of decline. The greatest period of decline, on a percentage basis, was the 1930s 'Great Depression' (Figure 5a) with an annual decline of 5.8%. Emergy

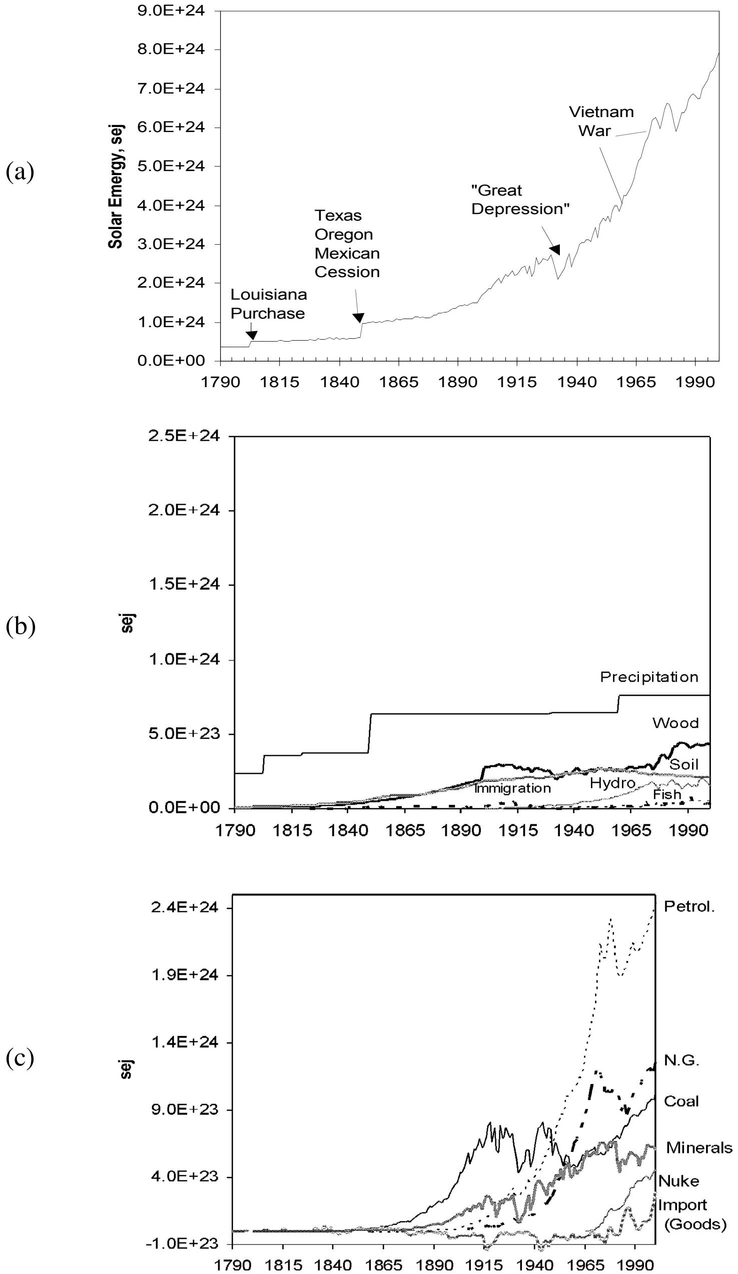


FIGURE 5. Historical solar emergy use in the U.S. (1790–2000), total (a), renewable (b), non-renewable (c).

use in the 1970s was turbulent with large intra-decadal swings and little change from beginning to end. Since 1982, emergy use increased steadily at a rate slower than the 1960s and a brief period of decline during the 1990–91 Gulf War recession. Since 1973, the mean growth rate has slowed from the country's average, which may indicate that the U.S. has crossed the inflection point of growth with future growth rates slowing.

Figure 5b and 5c break out the major components of total solar emergy use in the U.S. for the 1790–2000 period. Figure 5b shows the main renewable emergy inputs, while Figure 5c includes the most important non-renewable inputs. Precipitation has always been the largest renewable source of emergy to the U.S., while wood and soil consumption were historically the next most important renewables (Figure 5b). In the latter half of the twentieth 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 1920s when it was overtaken by petroleum (Figure 5c). Coal use was replaced by petroleum use as the number one non-renewable emergy input in 1949. Nine years later in 1958, natural gas use replaced coal use as the number two 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-powered electricity increased dramatically during its 35-year history 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, grew to be a substantial component of U.S. emergy consumption (Figure 5c). The solar emergy of non-fuel minerals peaked at about 12%, as a percentage of total solar emergy use, in the 1940–1950 period, but continued to provide 8% of total emergy consumption in 2000.

In the U.S., cumulative total solar emergy use grew continuously from 1790 to 2000 (Figure 6). 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/yr). In this sense the U.S., by consuming ancient stocks of fuels and minerals, has used the equivalent of 1074 years of renewable solar emergy in 210 years. Or, in other words, an average year of emergy consumption in the U.S. is equal to 5 years of renewable endowment.

The pattern of change in the ratio of U.S. emergy use to gross domestic product (emergy-to-$ ratio) was calculated for the period 1869–2000, but due to lack of

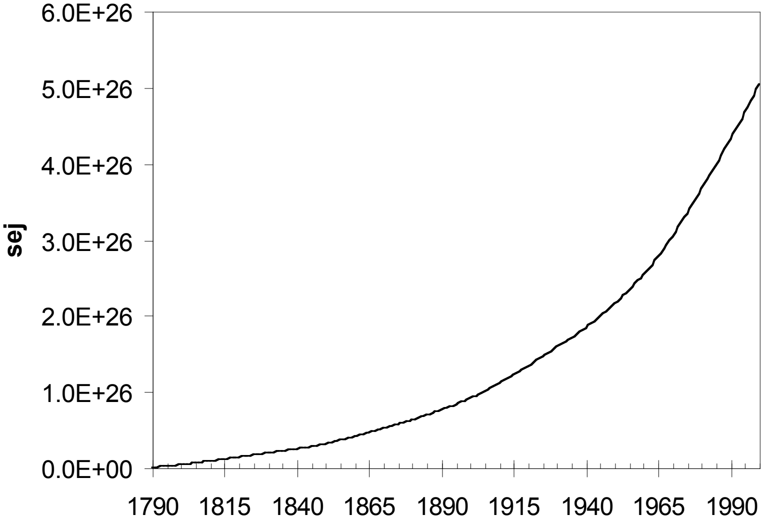


FIGURE 6. Cumulative total solar emergy use in the U.S. (1790–2000).

data on GDP for the earlier period (1790–1869), was modelled by hind-casting with a least-squares fit of the 1869–2000 data (Figure 5). The log transformed emergy-to-$ decreased linearly with time (Figure 7). For the 131-year period from 1869 to 2000, the emergy-to-$ showed a remarkable decrease of slightly more than two orders of magnitude. In 1869, the ratio was 150 E12 sej/$, but by 2000 had fallen to only 0.78 E12 sej/$. In 1790, we estimated each U.S. dollar was backed by 6030 E12 sej, nearly 8000 times its 2000 value.

The 'emergy-devaluation' of the U.S. dollar indicated that the circulation of money in the economy, as measured by gross domestic product, increased at a faster rate than emergy use. After the Korean War, from 1952 to 1971, the rate of change in emergy-to-$ was a consistent 0.25 E12 sej $\$^{-1}$ y^{-1} (Figure 7), which was slower than the high inflation period of the 1970's when the rate of decrease was 0.33 sej $\$^{-1}$ y^{-1}, but faster than during the 1990's when the decrease was only 0.04 sej $\$^{-1}$ y^{-1}.

The continuous devaluation of the U.S. dollar in terms of its emergy support is analogous to Bolin's observation as noted by Tainter and colleagues that the mass of silver in a Roman denarius declined from 3.6 grams in A.D. 1 to less than 0.1 grams in A.D. 269.[23] This form of 'debasement' allowed money supply to be increased using a conservative and relatively scarce material. In addition to the temporal emergy-devaluation of money, there also exists a spatial phenomenon whereby a gradient in emergy-to-$ is established between rural hinterlands and urban centres.[24] With less money circulating in rural regions relative to total emergy use, the emergy-to-$ ratio is higher in less developed areas than in cities. The same held true when Izursa and Tilley compared a less developed country (Bolivia) with a developed one (US).[25] Less developed countries have emergy-to-$ ratios up to an order of magnitude larger than developed countries. The general trend is for the emergy-to-$ ratio to decline as economies develop. It may be a general systems principle that the ratio of national metabolism to money circulation (i.e., gross national product) must decrease during economic development. If money circulation slows, then national metabolism declines (as was shown above for the 1930s Depression). An expansionist economy is hindered when money is in short supply. Alternatively, a faster rate of increase in GDP than in national metabolism is highly inflationary as was seen in the U.S. in the 1970s.

The more common explanation for the decline in the ratio of energy use to GDP is that it is due to improved 'economic energy efficiency'.[26] This argument ignores the expanding role that money plays in more and more types of economic exchanges as an economy develops. A rural inhabitant finds much sustenance without paying for it, whereas an urbanite must pay for most of the items and services they consume. In other words, during economic development, money is necessarily used to satisfy more material and life supporting needs. Only the reductionist-minded observer would ignore the fact that urban centres depend on huge flows of resources and energy from near and far-off rural areas. Thus, an increase in the scale of the economic activity is mistaken for efficiency improvements. This is an example of drawing an inconsistent and arbitrary analytical boundary.

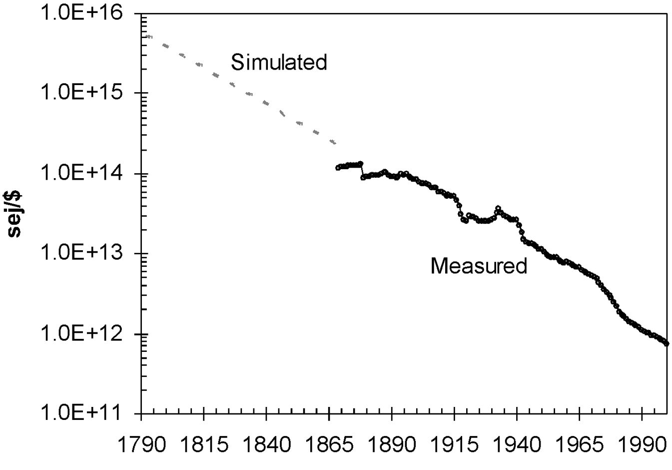


FIGURE 7. Measured and simulated solar emergy per U.S. dollar (1790–2000). (Note log scale for emergy-to-$)

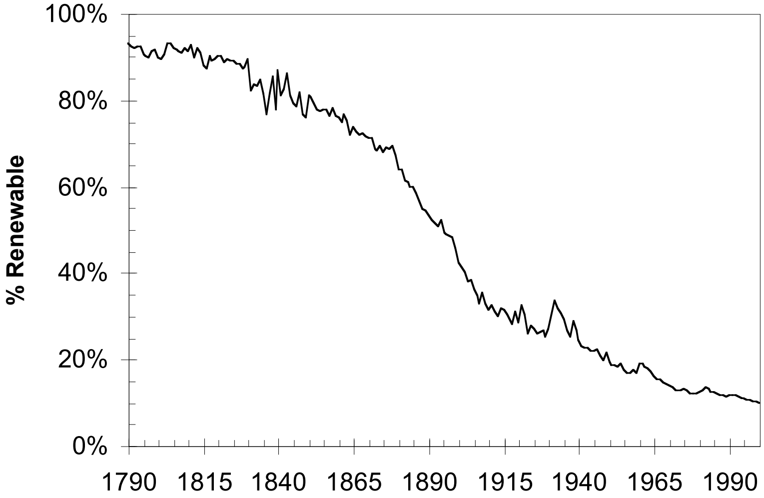


FIGURE 8. Historical percentage of total solar emergy use in U.S. derived from renewable sources (1790–2000).

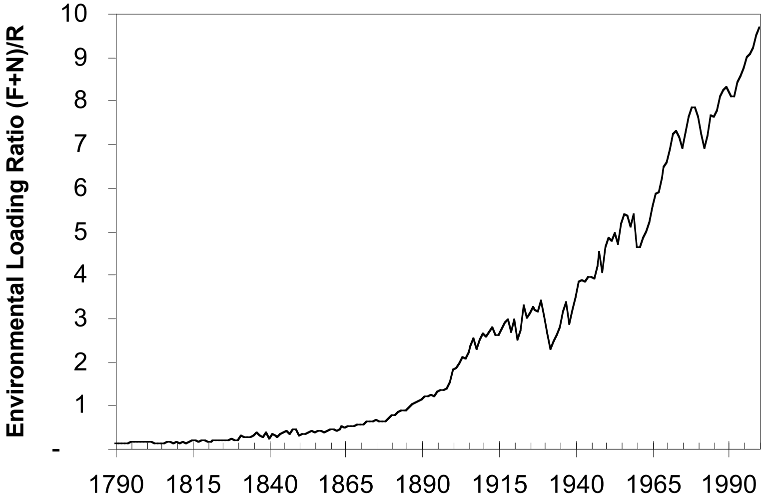


FIGURE 9. Historical Environmental Loading Ratio (ratio of non-renewable to renewable solar emergy use) of U.S. (1790–2000).

The percentage 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 8). The drop was heavily influenced by the emergence of fossil fuel use. The mean annual Environmental Loading Ratio of the U.S., a measure of economic intensity relative to the capacity of the environment to support that economic activity, steadily increased from 0.10 in 1790 to 9.7 in 2000 (Figure 9).

Both the percentage of solar emergy derived from renewable sources and the Environmental Loading Ratio indicated that the U.S. relied less and less on the free services of the environment for emergy supply as it developed. As fossil fuel inputs to the U.S. economy decline beyond 2000 and ‘alternative sources’ of energy fail to compensate as predicted by H.T. and Elizabeth Odum,[27] the Environmental Loading Ratio will begin to shrink and the country will be forced to obtain a greater percentage of its solar emergy from renewable supplies like forest and agriculture.

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 within a historically narrow range of 16,900 to 24,600 E12 sej with a mean of 22,100 E12 sej (Figure 10) for the next 70 years until 1960. The minimum occurred early in the ‘Great Depression’ in 1932. In the most

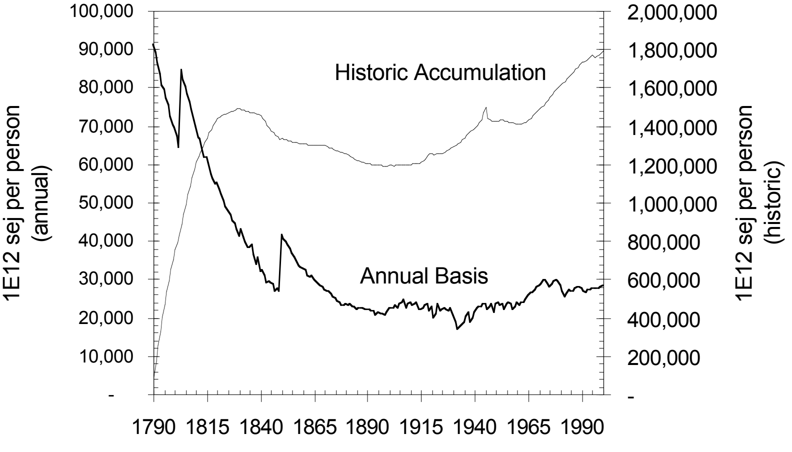


FIGURE 10. Per capita solar emergy on an annual basis (annual solar emergy per person) and historic accumulation basis (cumulative solar emergy use per person).

recent period (1970–2000), the average rose to 27,800 E12 sej with a maximum of 29,800 E12 sej in 1978. Most recently, in 2000 it stood at 28,200 E12 sej.

While an annually based per capita index may capture total resource use and indicate well-being, a new per capita emergy index is proposed which uses the cumulative solar emergy used since the country began. I call this the per capita cumulative consumption of solar emergy (CCSE). I 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 10). 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.

What can the per capita CCSE tell us? People living today must attribute a large proportion of their knowledge, wealth and affluence to the work of their forbears. The CCSE could be particularly useful for comparing the affluency 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 an annual basis. Although their annual per capita use is lower than the U.S., these countries continue to wield global influence, often through culture, language, international institutions and academic knowledge. Britain, for example, through its colonisation and intimate influence of a vast expanse of the world over the past centuries, presumably accumulated a large amount of solar emergy (the calculation does not exist to our knowledge) and continues to influence a significant portion of the world's flow of solar emergy. Emergy used in the past was invested in institutions of learning and government, which serves as a stock of intellectual capital that is used for control of today's society. Thus, historic emergy accumulation is a means of measuring the value of information stored 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 historic use of solar emergy stored? Is it in written manuscripts, periodicals and books? Is it stored in the customs and mentality of the people? In technologies? I believe it is ultimately stored as knowledge capital in the high quality mental capacities of humans and their various devices for storing information. As long as there is a temporal continuum that connects historic events to the people of the current age, then most, if not all of the historic use of solar emergy accumulates as stocks of information wealth. 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 which 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 during its first 10 years of existence, but suddenly finds large readership in 1990. In the time interval between 1980 and 1990, the emergy stored in the content of the paper is not contributing to knowledge production so it should not be added to emergy accumulated. However, after 1990 it is contributing significantly to scientific progress, which indicates that its emergy should be added to accumulated emergy. A question in dynamic emergy accounting is to determine the length of the lag period, if it exists at all.

The preceding account of the history of national metabolism in the U.S. has shown that it grew exponentially during the country's existence, but showed signs of slowing down after 1982. Non-renewable resources rapidly increased in importance to the country, surpassing the contribution from renewable sources in the late nineteenth century. Per capita national metabolism was greatest at the country's founding, declined during the nineteenth century, oscillated within a narrow range for the early half of the twentieth century, grew significantly during the decade of the 1960s, retracted over the next decade, and finally reached a steady-state during the last two decades of the twentieth century (Figure 10).

Solar Transformities 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 11). The U.S. instituted a Patent Office shortly after forming its constitutional

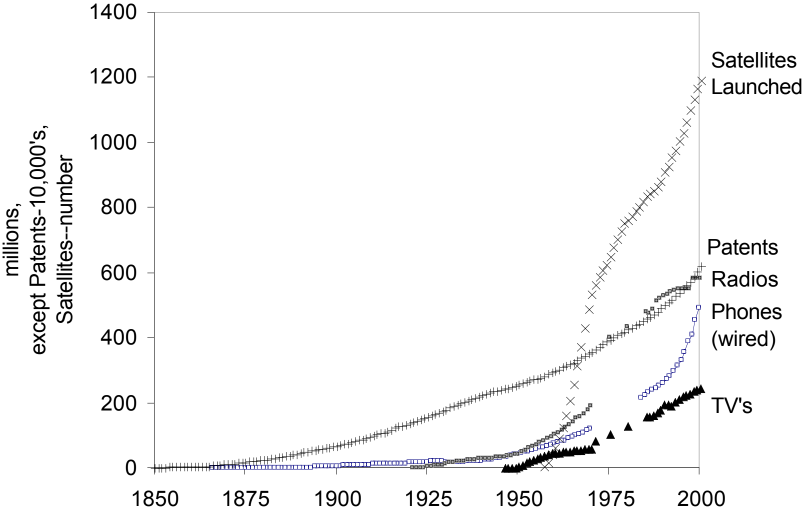


FIGURE 11. Historical rate at which popular technologies accumulated in the U.S. from 1850 to 2000 (television sets, wire-based telephones, radio sets, cumulative patents issued since 1780, cumulative geostationary communication satellites launched successfully).

government in the late 1700s. In the first year there were three patents issued; 210 years later there were a record 158,014 issued in a single year (Figure 2). Figure 11 shows that patent growth has accelerated, especially in the late 1990s, presumably fuelled by the inter-networking of computers known as the World Wide Web. The typical US household has 5–6 radios and nearly two TVs. 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 1200 working geostationary communication satellites in orbit (Figure 11).

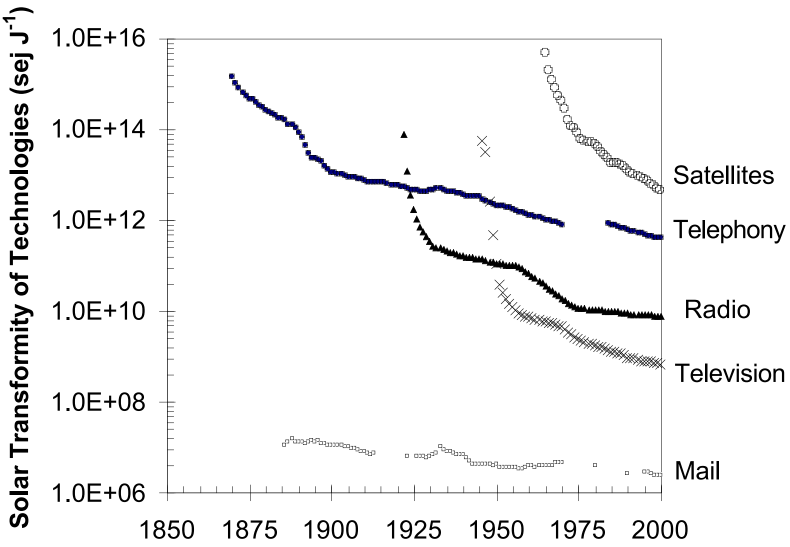


FIGURE 12. Time series of the solar transformity of communication satellites, telephony, radio, television, and mail.

Figure 12 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 4700 E12 sej/J in 1965 to 4.8 E12 sej/J in 2000. The solar transformity of telephone communication dropped more than two orders of magnitude during its first thirty years, from 1410 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 transformity of radio output decreased by over two orders of magnitude during its first ten years of existence, but only dropped 9% during the most recent 10 year period (1990–2000) to a value of 8.11 E9 sej/J. Although the U.S. Postal Service was created when the country began, we began our estimate of the solar transformity of mail in 1880 due to data availability. 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. Regardless, the solar transformity of mail decreased from 15 E6 sej/J in 1890 to 2.5 E6 sej/J in 2000 (83%).

H.T. Odum proposed that the solar transformity measured the position that a form of energy occupied in the global hierarchy of energy transformation processes.[28] Forms of energy small in quantity (e.g., human brain power) are often high in quality. Higher quality energy forms produce more effect on system performance per unit of their energy 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 from high to low as: telephony, radio, television and mail (Figure 12). Satellites are the most global of the communication devices evaluated, allowing information to be communicated between any two points on Earth with only split-second delay. Mail, on the hand, is also used to communicate globally, but its transmission rate is several orders of magnitude slower than satellites (~100,000 seconds versus 1 second). The rank order of the technologies fits our preconceived notions, except for TV and radio. We would have expected TV to have a higher solar transformity than radio mainly due to the apparent influence TV has had on American culture and the typical citizen's daily intake of information gathered through TV.

The most remarkable feature about the historical change of the technologies' transformities was their common regression toward lower levels (Figure 12). 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 solar transformity 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 solar transformity larger. The increase in units would also have allowed for 'economies-of-scale' to be achieved; lowered total resource consumption per a unit operated. For example, the nation's number of TVs (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.

More importantly, the fact that the solar transformity of each technology approached a minimum as it declined indicates that there are system limits to the amount of solar emergy required to operate communication technologies. In other words, the 'resource efficiency' (total resource output per unit of input, which is the reciprocal of solar transfomity) of operating and maintaining each communication technology improved less and less each year. This indicates there is a thermodynamic limit to how little solar emergy is required to transmit information via each technology. This limitation is analogous to Vaclav Smil's observation that the energy efficiency of steam generators, metal production and nitrogen fertiliser manufacture approached maxima as each evolved.[29] This evidence contradicts the assertion by technical optimists, such as Julian Simon and Amory Lovins, that efficiency can be improved endlessly.[30]

A Coupled Future: Energy Supply and Technological Innovation

Does modern information technology increase a nation's solar empower without necessarily increasing its power consumption? In other words, do modern technologies increase the flow of high quality energies and therefore, standard of living, without increasing the use of energy? This is a type of 'empower efficiency' (i.e., ratio of total empower consumed from all sources to total energy used) for a nation? Does technology ultimately allow us to do more with less energy? Or does increased use of technology cause more power consumption? This is difficult to answer for the U.S. because both power and empower consumption continuously increased through the year 2000.

However, these questions can be framed by two hypotheses about the temporal behaviour of a nation's power spectrum, shown in Figure 13, which is a plot of the log transformed use of an energy as a function of its log transformed solar

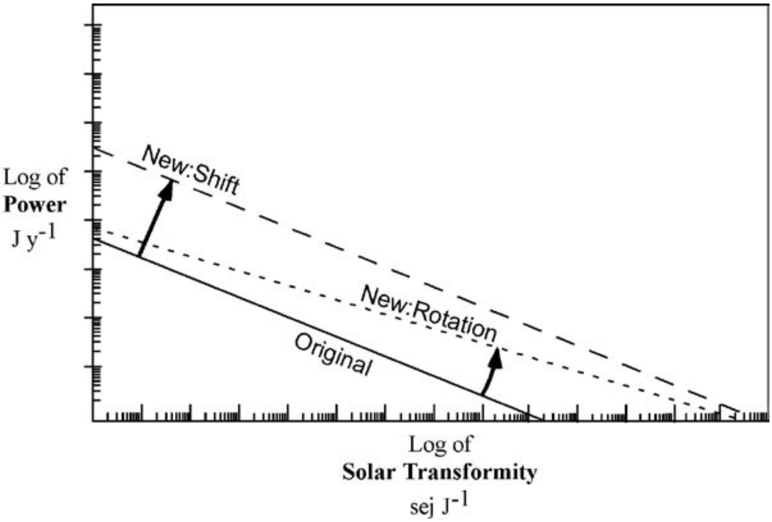


FIGURE 13. Two hypotheses about the temporal dynamics of power spectra as system empower increases.

transformity. Low transformity forms of energy (e.g., solar radiation, wind), which are plentiful but diffuse and difficult to collect for direct human power consumption are on the left, while high transformity forms of energy (e.g., satellite signals, hydrogen gas, college lecture), which are rare but influential to system behaviour, are on the right in Figure 13.

In the first hypothesis, a change from the original spectrum to a new spectrum occurs as a complete 'shift' but with no change in slope. In the second hypothesis, the new spectrum is generated by a 'rotation' about the y-intercept. In each hypothesis, 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. The rotation hypothesis fits the notion that technology improves the efficiency of resource use. In a shifted spectrum, high and low transformity energies are increased in similar proportions, which would be the case if 'resource efficiency' were stagnant.

Whether either hypothesis is correct needs to be tested empirically. If either were proven valid then the role of technology and technological innovation in a future scenario of energy limitation could be gauged. Under the rotation hypothesis, technological innovation can continue if national metabolism reaches steady state. The shift hypothesis says that technological innovation can only occur when national metabolism increases.

In an Odumesque 'prosperous way down' perspective,[31] the important question could be framed as, 'how does the power spectrum (Figure 13) behave when resource availability and use shrink?' Theoretically the higher transformity units have longer turnover times than lower transformity ones, which allows the knowledge of how to employ a technology to remain present years after the physical apparatus has disappeared. This fits with Odum's idea that shared information has a longer turnover time.[32] Memories remain long after the creating event disappears. The longer turnover time of higher transformity items may force the power spectrum of a system to exhibit wave properties as an economy expands, plateaus, and declines. That is, during an early period of an expanding economy (e.g., the US in the 1700s) the wave starts on the left of the spectrum with relatively high use of low transformity energies (e.g., water), but relatively little information flow (think 'Pony Express'). As the economy continues to expand the wave propagates to the right through mid-level transformities (e.g., fossil fuels) and high transformity flows increase measurably (e.g., telegraph begins). At some point, shortly before, during or shortly after peak national metabolism, the wave reaches far to the right to achieve a maximum solar transformity. After peak, the wave may remain high on the high transformity end for only a short time, while the low transformity region shrinks. Eventually the whole spectrum shrinks as power availability drops and the economy reverts to a renewable basis with a reduced per capita national metabolism. Much, but not all of the high transformity technology will vanish. The remaining technology will be that which marginally improves the efficiency of renewably powered processes. A timely question for modern society is, 'are we creating the most memorable parts of the system?'

NOTES

[1] Julian Lincoln Simon, *The Ultimate Resource 2* (Princeton, N.J.: Princeton University Press, 1996), p. 481.

[2] Amory B. Lovins, 'More profit with less carbon', *Scientific American*, **293**(3) (2005): 74–82.

[3] Joseph A. Tainter, *The Collapse of Complex Societies* (Cambridge: Cambridge University Press, 1988); Joseph A. Tainter, T.F.H. Allen, and T.W. Hoekstra, 'Energy transformations and post-normal science,' *Energy*, **31** (2006): 44–58.

[4] Richard G. Wilkinson, *Poverty and Progress: An Ecological Perspective on Economic Development* (New York: Praeger Publishers, 1973).

[5] J. Diamond, *Guns, Germs, and Steel: The Fates of Human Societies* (New York: W.W. Norton & Company, 1997), p. 494.

[6] Howard T. Odum, *Environment, Power, and Society* (New York: John Wiley & Sons, 1971) p. 151.

[7] David Tilley, unpublished computer simulations.

[8] Richard Heinberg, *The Party's Over: Oil, War and the Fate of Industrial Societies* (Gabriola Island, British Columbia: New Society Publishers, 2003); James Howard Kunstler, *The Long Emergency: Surviving the Converging Catastrophes of the Twenty-first Century* (New York: Atlantic Monthly Press, 2005).

[9] David Tilley, unpublished computer simulations.

[10] H.T. Odum, *Environmental Accounting: Emergy and Environmental Decision Making* (New York: John Wiley & Sons, Inc., 1996).

[11] H.T. Odum, 'Self organization, transformity, and information', Science **242** (1988): 1132–9.

[12] David R. Tilley, 'Emergy basis of forest systems' (Ph.D. diss., University of Florida, Gainesville, 1999), p. 298, available on-line <http://www.bre.umd.edu/tilley.htm>; David R. Tilley and Mark T. Brown, 'Dynamic emergy accounting for assessing the environmental benefits of subtropical wetland stormwater management systems', *Ecological Modelling*, **192** (2006): 327–61; Odum, *Environmental Accounting.*

[13] J. Shinker, Global Climate Animations, Dept. of Geography, University of Oregon (2003) <http://geography.uoregon.edu/envchange/clim_animations/>. Last visited January 2004.

[14] S.B. Carter (ed.), *Historical Statistics of the U.S., Colonial Times to 1970*, electronic edition (Cambridge: Cambridge University Press, 1997); U.S. Census Bureau, *Statistical Abstract of the United States,* CD-ROM (Washington, DC: U.S. Census Bureau, Data User Services Division, 2002).

[15] Carter, *Historical Statistics.*

[16] Carter, *Historical Statistics*; J.L. Howard, *U.S. Timber Production, Trade, Consumption, and Price Statistics 1965–1997* (Madison: U.S. Forest Service, General Technical Report FPL-GTR-116, 1999), p. 76.

[17] Tilley, 'Emergy basis of forest systems'.

[18] Carter, *Historical Statistics*; U.S. Census Bureau, *Statistical Abstract of the United States, 1992* (Washington, DC: U.S. Census Bureau, 1993).

[19] Odum, *Environmental Accounting*.

[20] Sources: (a) Odum, *Environmental Accounting*; (b) Wilkinson, *Poverty and Progress*; (c) H.T. Odum and M.T. Brown, *Methods for Evaluating Ecological Engineering*, Final Report to National Science Foundation #8818284 (University of Florida, Gainesville: Center for Environmental Policy, 1993).

[21] U.S. Census Bureau, *Statistical Abstract of the United States, 1972* (Washington, DC: U.S. Census Bureau, 1973); U.S. Census Bureau, *Statistical Abstract of the United States, 1981* (Washington, DC: U.S. Census Bureau, 1982); Carter, *Historical Statistics*.

[22] Odum and Brown *Methods for Evaluating Ecological Engineering*; U.S. Census Bureau, *Statistical Abstract, 1992*; U.S. Census Bureau, *Statistical Abstract,* CD-ROM; Carter, *Historical Statistics*..

[23] Tainter, Allen, and Hoekstra, 'Energy transformations'.

[24] Shu-Li Huang and Chia-Wen Chen, 'Theory of urban energetics and mechanisms of urban development', *Ecological Modelling*, **189** (2005): 49–71.

[25] Jose-Luis Izursa and David R. Tilley, 'Emergy Analysis of Bolivia's Natural Gas', in M.T. Brown, D. Campbell, V. Comar, S.L. Huang, T. Rydberg, D.R. Tilley and S. Ulgiati, eds, *Emergy Synthesis 3: Theory and Applications of the Emergy Methodology* (Gainesville, FL: Center for Environmental Policy, 2005).

[26] Lovins, 'More profit'.

[27] Howard T. Odum and Elisabeth C. Odum, *A Prosperous Way Down: Principles and Policies* (Boulder: University Press of Colorado, 2001). A condensed version of the Odums' work recently became available: Howard T. Odum and Elisabeth C. Odum, 'The prosperous way down', *Energy* **31** (2006): 21–32.

[28] Odum, 'Self organization'.

[29] Vaclav Smil, *Energies: An Illustrated Guide to the Biosphere and Civilization* (Cambridge, Massachusetts: MIT Press, 1999).

[30] Simon, *The Ultimate Resource 2*; Lovins, 'More profit with less carbon'.

[31] Odum and Odum, 'The prosperous way down'.

[32] Odum, *Environmental Accounting*.