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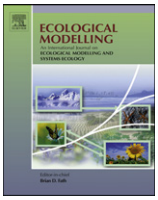

Predicting national sustainability: The convergence of energetic, economic and environmental realities

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ABSTRACT

The "constraint space" dictated by energetic, economic and environmental realities on scenarios for future organization of humanity and nature is explored from the perspective of the energy and resources driving economies. Net energy of energy sources is presented as an index (Emergy Yield Ratio; EYR) that must be evaluated for energy sources to better understand their potential contributions to society, but more important, as an indicator of the changes needed in the future if lower net yielding sources are to be relied upon. An aggregate EYR was calculated for the USA economy and shown to have decreased by 38% since 1950, from 11/1 to 6.8/1. Several measures of efficiency at the scale of national economies are explored and the data suggest that the most efficient economies are also the most energetically intense (as measured by empower intensity). An index of environmental loading is suggested as a measure to evaluate environmental efficacy. An obvious outcome is that the smallest most energetically intense countries have the highest environmental loads, and those with large land area and/or continental shelves have the lowest ratios. An Emergy Sustainability Index (EmSI) is defined, computed for countries, and proposed as a multi-dimensional measure of long-term sustainability. The most sustainable economies are those with the highest EYR and lowest environmental loads.

1. Introduction

Considering the future. . .one must pause to reflect on where we are heading and what things affect how we will get there and for that matter what "there" is. There are many who suggest that the future will be characterized by lower energy availability (see for instance Campbell, 1997; Duncan and Youngquist, 1999; Aleklett and Campbell, 2003; Banks, 2004; Hallock et al., 2005; Greene et al., 2007), reasoning that global fossil fuel storages are just that, storages, ultimately limited in total amount, and as a consequence the future will hold less energy for the affairs of humans. In fact, many suggest that the known storages of conventional fossil fuels have already "peaked" and to make matters worse, the world's appetite has not, causing a collision of growing demand and decreasing supply.

To be fair, we must also put forward that there are those who suggest there are no limits (Johnson, 2006), that the future will be one of increasing supplies of energy and ever more sophisticated technologies. Lynch (1999) suggested ". . .the extremely pessimistic forecasts of Campbell and his colleagues are based on bias and inaccurate methodologies, and cannot be taken seriously. No non-renewable resource has "run out" or seen its price trend upwards more than temporarily in modern times.". . .as if the historical abundance of fossil fuels was a good predictor of the future. Still others suggest that while availability may be declining and energy supplies may dwindle, human enterprises will exhibit increasing efficiencies in the future (IWG, 2000), effectively offsetting any limits that may result from dwindling supplies (Brown et al., 2001; Lenssen and Flavin, 1996). Finally, there are those who suggest technology is the future. . .that humans will develop a technological fix to dwindling supplies, converting sunlight or biomass, or some other ubiquitous material (water for instance) into energy, resulting in essentially unlimited supplies (see for instance Hisschemoeller et al., 2006; Maack and Skulason, 2006; McDowall and Eames, 2006; Penner, 2006).

No matter which reality one projects for the future, there are constraints that should be understood or at least addressed if we are to have a clear vision of what the future holds. Energetic and environmental realities form a constraint space on the future much like that depicted in Fig. 1, which shows three axes, each with its own scale. Whether depicting a single technology or the suite of technologies and production functions that make up an economic system the graph describes the relationships between energetic efficiency, environmental costs and economic effectiveness. Here,

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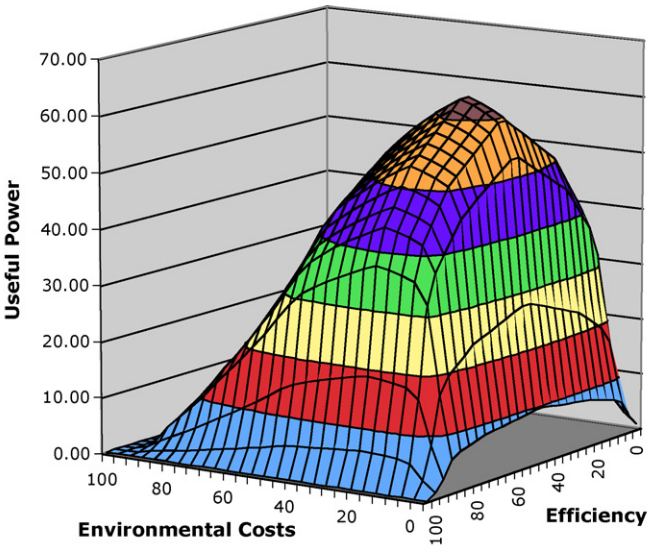

Fig. 1. Three-dimensional graph of the relationship between environmental costs, energetic efficiency, and useful power.

economic[1] effectiveness is defined as the output of useful power. Energetic efficiency is the ratio of outputs to inputs and scales possibility; maximum useful power is obtained at 50% efficiency Odum and Pinkerton (1955). Environmental costs are the consumption of natural capital and use of environmental services where useful power drops off rapidly as environmental costs increase.

1.1. Energy quality

Before proceeding to the main thesis of this article, namely the impact of energetic, economic and environmental realities on future scenarios for humans and nature in the face of dwindling supplies of rich fossil fuels, it is necessary to first provide some background. We begin by discussing "energy quality".

Not long ago considered heretical, but increasingly more accepted is the somewhat counter intuitive but non-the-less important fact that not all energy is the same. We term the dissimilarity between forms of energy, differences in their QUALITY. These differences are expressed in the reality that calorie for calorie not all forms of energy have the same ability to do work. Odum (1971, 1973, 1983, 1987, 1988, 1996, 2007) understood that because of these differences "quality corrections" were necessary if one were to compare one form with others. Reflecting on these differences, Odum (1983) was one of the first to point out the fallacies of energy technologies that promised unlimited energy for society from the sun since the sun was too dilute and the energy cost of concentration was too high for it to have much net yield once the cost of concentrating technologies was subtracted.

By now it is well understood by many scientists that energies of different forms have somewhat different abilities to perform work. Such phrases as "metric tones of coal equivalent" are now commonly used to express various energies of different forms in coal equivalent energy by equating their heat contents. Cleveland (1992) understood that energy quality correction was necessary to evaluate net energy, saying "...different types of energy have different abilities to do work per heat equivalent" and then suggested an economically derived quality correction for energies used in economic work processes (i.e. industrial processes).

1.2. Quality is system dependent

The flexibility of different forms of energy is somewhat system dependent. What may be appropriate and usable within one system may not be within another. For instance sunlight is appropriate for photosynthesis, but not for use in an automobile (unless of course we upgrade it to electricity) and vice versa; fossil fuel is appropriate to burn in an internal combustion engine, but is not appropriate for photosynthesis. Appropriateness in this case is related to the form the energy takes and might be thought of as related to concentration in time and space. Another way of thinking of it is intensity, measured in joules per kg or joules per unit volume (or energy density).

If we are to understand how the biosphere works and understand human's place within, then we must consider more than one level or scale of the geobiosphere at the same time (i.e. we must maintain a whole systems perspective). When scales are combined it is quite apparent that many different forms of energy also are combined as necessary inputs to system processes. In order to combine scales in the same analysis it is clear that a very different approach to defining energy and ability to do useful work is necessary. So we introduce the concept of energy quality and define it as the expression of different forms of energy in terms of one form through conversion to equivalent units of that form. It is through the conversion that the difference in quality is determined. Say for instance if it takes 4 units of coal to make 1 unit of electricity, then in this case we can say that the quality of electricity is four times that of coal.

In this way, the use and transformation of energy sources is system dependent; where the appropriateness of an energy in a particular system is dictated by its form and is related to its concentration. The processes of the geobiosphere are more than just thermodynamic heat engines. Therefore, the use of heat measures of energy that can only recognize one aspect of energy, its ability to raise the temperature of things, cannot adequately quantify the work potential of energies used in more complex processes of the biosphere. In the larger biosphere system, energies should be converted to units that account for multiple levels of system processes, ranging from the smallest scale to the largest scales of the biosphere, including processes other than heat engine technology.

1.3. Emergy and energy quality

In this paper we use emergy (defined as the quantity of energy of one type require to make something) to express resources, goods and services in units of the same quality. For a full discussion of emergy, terms, and methods of evaluation and accounting one can begin with Odum's 1996 book *Environmental Accounting* or any of numerous articles by the author as follows: Brown and Ulgiati (1997, 1999, 2001, 2004, 2007) and Ulgiati and Brown (1998, 1999, 2000).

Emergy intensities (EIs) are intensity factors that are calculated as the total amount of emergy required to make a product or service divided by the available energy of the product (resulting in a *transformity*) or divided by the mass of the product (resulting in a *specific emergy*). Fig. 2 illustrates the method of calculating an EI. The transformity of the product is the emergy of the product divided by the energy of the product (units are sej/J). If the output flow is in mass, then the specific emergy of the product is the emergy of the output divided by the mass (units are sej/g). Emergy intensities are global measures of efficiency.

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[1] We use economics in its most basic definition. . .the production, distribution and consumption of resources, goods, and services. Thus, economic effectiveness is the production, distribution and eventual consumption per unit time, which in its most general sense, if resources, goods and services are expressed in units of energy, can be thought of as useful power (energy per unit time).

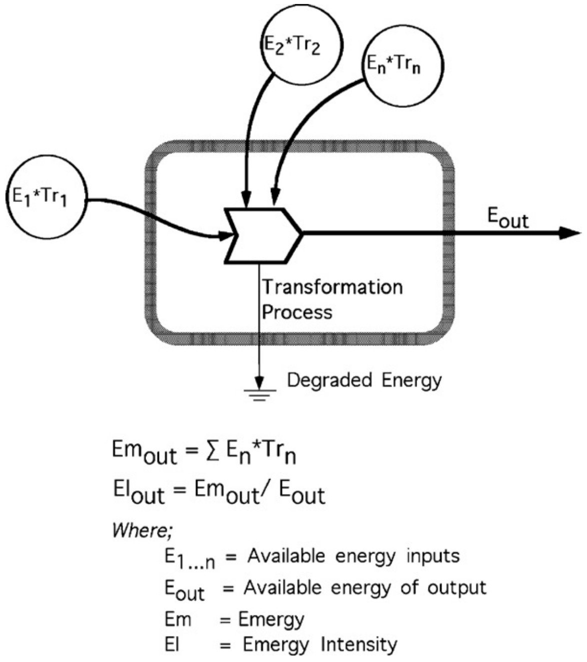

Fig. 2. Definition of emergy intensity. By definition the emergy of a product or process is the sum of all the inputs expressed in the same quality.

1.4. Net energy and emergy yield ratio

Net energy of any process including energy sources is calculated using an Emergy Yield Ratio (EYR) (see Odum, 1976; Brown and Ulgiati, 1997) which is the net contribution of an energy source to the economy. Hall et al. (1986) introduced a similar concept called Energy Return on Investment (EROI), although different from EYR in that it does not include quality correction and other inputs such as labor and environmental contributions. The EYR as its name implies, is the ratio of the yield from a process (in emergy) to the costs (in emergy) (Fig. 3). The yield from this process is the sum of the input emergy from all sources: the environmental renewable source on the left (R), the non-renewable storage (N), and the two purchased flows from the right (F). In the case of fossil fuels, there is little input from renewable sources since the vast majority of the input comes from deep storages in the earth. The EYR is the ratio of the yield (Y) to the costs (F) of getting it. The costs include energy, materials, and human service purchased from the economy all expressed in emergy.

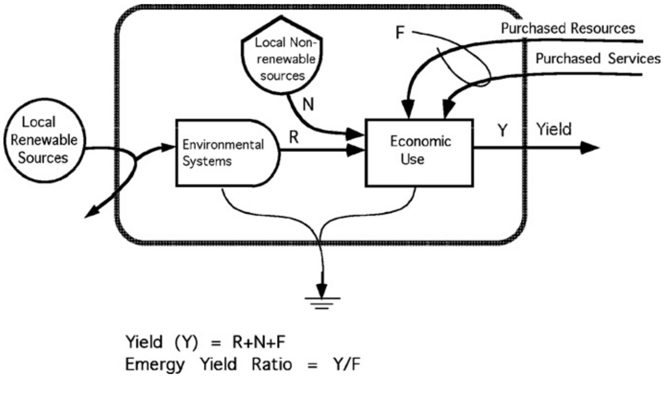

Fig. 3. Emergy Yield Ratio (EYR) is the yield of a process (expressed in emergy) divided by the purchased goods and services (also expressed in emergy) necessary to produce the yield (after Brown and Ulgiati, 1997).

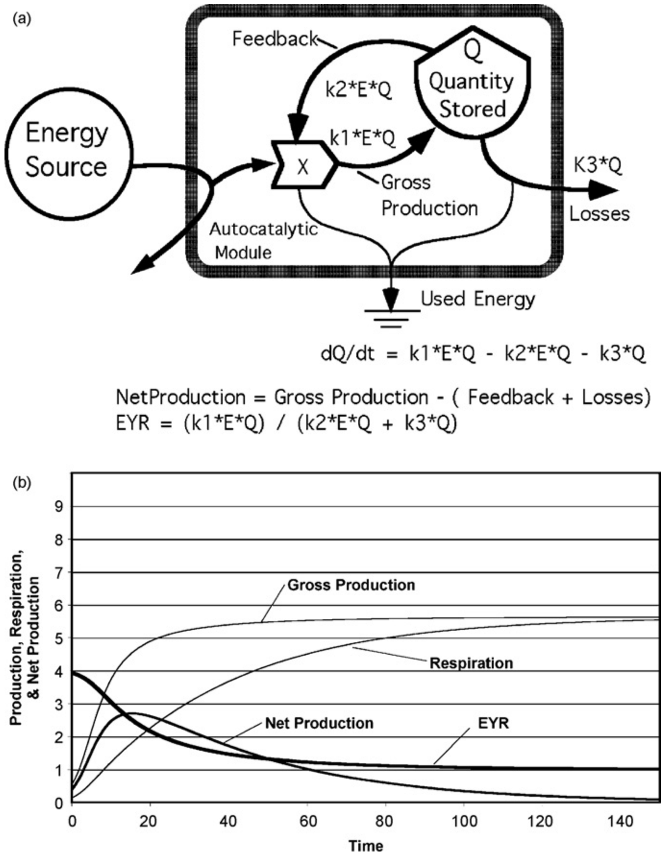

Fig. 4. Simulation model of autocatalytic system illustrating the concept of net production (or net contribution to growth). (a) Diagram with equations; (b) resulting simulation graph. Net production is the difference between gross production and respiration. Emergy Yield Ratio (EYR) is the ratio of the inflows to the outflows from Q.

The concept of net emergy yield is central to understanding what can and cannot be done with energy sources in relation to human development and sustainability. The ecological concept of "net production" is widely used as a measure of overall development potential in ecological systems. A macroscopic minimodel of ecosystem growth is given in Fig. 4. During early stages of development, ecosystems exhibit large net yields from productive autocatalytic processes. Autocatalytic cycles contribute to growth and development if their yield is greater than their cost (i.e. their net yield is greater than 1.0). In ecosystems, net contributions from some productive processes are used to reinforce other interactions and processes that in turn contribute to and/or augment flows of energy through positive feedback thus facilitating growth and development. Key to identifying when growth diminishes and eventually stops is when costs of sustaining system processes increase and eventually equal productive processes. The graph in Fig. 4 shows production verses time that results from simulation of the system model in the top of the figure. The net contribution of the energy source to growth and development is the area between the two lines. The net contribution is always greatest in early stages of development and declines as the energetic costs of processes and organization (overhead) increase with increasing quantities of structure.

Since the concept of emergy yield seems applicable to all systems, its logical that it also should be applicable to the processes of energy production, which drive economic sectors and human societies. When applied to the human economy the concept suggests two important caveats. First, an energy source must be able to provide a net contribution to the economy of the larger system

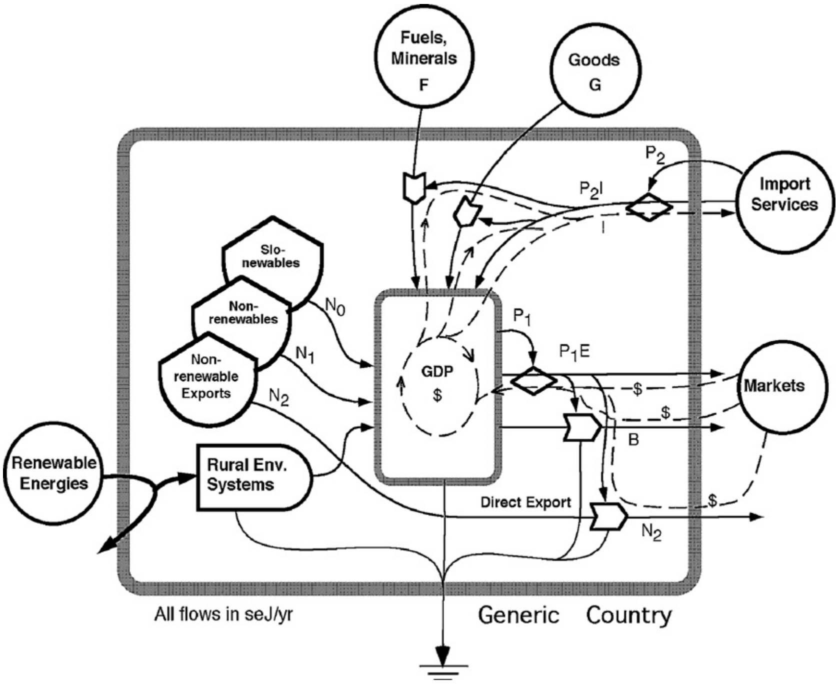

Fig. 5. Emergy flows supporting a national economy including renewable sources (R), non-renewable (N_1) and slowly renewable (N_0), imported fuels and minerals (F), imported finished goods (G), and imported services (P_2I). Direct exports of non-renewables (N_2) are not used directly within the economy, however they generate income from their sale. Total emergy use is called Gross Emergy Product (GemP) and is defined as the sum of ($R + F + G + P_2I + N_0 + N_1$) (after Odum, 1996).

in which it is embedded, i.e. it must provide more energy than it costs to extract and process it. Second, the behavior of the simulation models tells us that with time net energy declines as the costs (overhead) increase.

1.5. Emergy measures of national intensity and efficiency

Given in Fig. 5 is a generic systems diagram of a national economy that is helpful in visualizing the flows of emergy, materials and money used to describe emergy measures of national economies. Sources of emergy from outside that cross the system boundary include: renewables (R), fuels and minerals (F) and goods (G), as well as the services embodied in these imports (P_2I). Sources of emergy derived from storages within the country include: (N_0) “slo-newables” (slo-newables are resources that are used faster than they are renewed such as soils or forest biomass harvested at unsustainable rates) and (N_1) non-renewable resources (fossil fuels and minerals). Exports from the country include: services and labor (P_1E) embodied in finished products (B), and non-renewable resources (N_2) that are exported without upgrading in the economy. The circulation of money within the economy, the Gross Domestic Product (GDP) represents a monetary measure of the output. Total emergy use in the economy is the sum of all the inputs ($R + F + G + P_2I + N_0 + N_1$).

We define a new term based on the term used for the monetary value of a nation’s total production. The economic term, Gross Domestic Product (GDP) is defined as the market value of all final goods and services produced within a country in a given period of time (generally 1 year). We define Gross Emergy Product (GEmP) as the emergy value of all goods and services produced within a country in a given period of time, and by definition is equal to total emergy use in the economy.

Several indices are used to compare emergy intensity of national economies. Intensity of emergy use can be viewed in several ways: over space, relative to size of economy, and relative to population. Emergy intensities of national economies are the result of summing all emergy use to obtain the GEmP and then dividing by area, population, and GDP of each country. Since GEmP is emergy use per unit of time it is also empower (emergy per unit time).

- Areal Empower Intensity (AEI: sej year^{-1} m^2) – An index of the GEmP per unit area. Areal empower intensity is a function of both total annual emergy use (GEmP) and size of country. It results from summing all emergy inputs on an annual basis to obtain total annual emergy use and then dividing by the area of the country.
- Empower Per Capita (EPC: sej/capita) – The ratio of total emergy use (GEmP) within the economy to the population.
- Empower Intensity of Market Value (EIMV: sej/currency unit) – As the name implies this is the ratio of empower to market values (measured in currency). When calculated for a national economy it is the ratio of total annual emergy use (GEmP) to Gross Domestic Product (GDP). While it is understood that the use of GDP as an indicator of well-being has been questioned, we are not using GDP as an indicator of well-being, but instead using it as an index of currency circulation. Since money and emergy circulate counter current to each other, the EIMV index when calculated for an entire national economy is also a measure of the buying power of its currency. A higher number indicates more emergy use per unit of currency circulation.

In addition to the indices of emergy intensity, an index of national economies that relates the total emergy use to their indigenous non-renewable resources provides insight into the use of indigenous sources in the provision of resources, goods and services to the population. The index of national empower yield is as follows:

- National Empower Yield Ratio (NEYR) – For a national economy the NEYR is the ratio of the total annual emergy use (GEP) in the economy to the non-renewable emergy use from indigenous sources (N_0 and N_1 in Fig. 5). It is an indicator of GEP that is derived from the investment of local non-renewable resources.

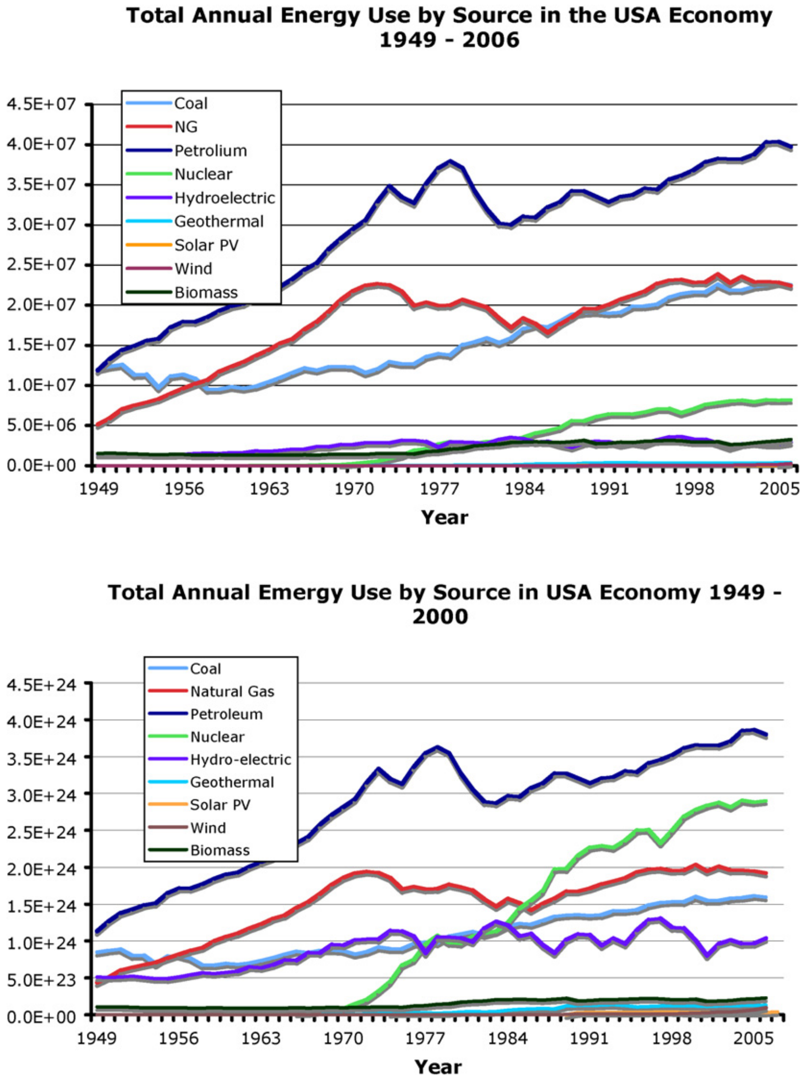

Fig. 6. Total annual energy use (TOP) and total annual emergy use (BOTTOM) in the USA economy 1949–2005. A significant difference in the contributions from nuclear and geothermal is evident when energies are corrected for quality as shown in the bottom emergy use graph. The following transformities were used to evaluate each source in emergy: coal = 67,100 sej/J; natural gas = 81,000 sej/J; petroleum = 91,600 sej/J; nuclear = 335,000 sej/J; hydroelectric = 340,000 sej/J; solar PV = 500,000 sej/J; wind = 350,000 sej/J; biomass = 66,000.

2. Emergy driving national economies: the USA as an example

2.1. Contributions of emergy sources to USA economy

The graphs in Fig. 6 show the contributions from different sources to the total energy (top) and emergy (bottom) mix of the USA economy using data from US Energy Information Administration (2007). When corrected for energy quality and expressed in emergy (bottom) the contributions of individual sources change in significance. Emergy contributions are largest from petroleum and natural gas, however, beginning in 1970 nuclear power has had increasing contributions to the economy, and today is the second largest contributor. Since the contributions from nuclear and hydroelectric sources are in the form of electricity, when corrected for quality, their overall contribution is much greater than when expressed in BTU's of thermal energy.

This is a most interesting consequence of quality correction. It is an often-quoted number that nuclear power provides about 12% of current energy production in the USA, but when expressed on a quality corrected basis nuclear power accounts for 22% of total energy production.

2.2. EYR of energy sources

Critical to continued prosperity, apparently the net yields from fossil fuel energy sources that drive our economy are declining. As the richest and largest oil fields are tapped and the remaining energy gets harder to find and even harder to drill for, the energy costs of obtaining oil and gas rises. As these limits are felt throughout modern economies, society looks to alternative sources; wind, waves, tides, solar, biomass, ethanol, etc. The graphs in Figs. 7 and 8 show typical EYRs for various energy sources used in modern economies. In Fig. 7 conventional non-renewable sources are shown, and in Fig. 8 some of the so-called renewable energies are shown. It is imperative that the net contributions of proposed new energy sources be evaluated and all costs included. Many of the so-called renewable energy sources are actually guzzlers of fossil fuels. Take for instance proposed corn to ethanol programs. Evaluations over the last decade continue to show EYRs of less than 2–1 (see for example: Giampietro et al., 1997; Ulgiati, 2001; Pimentel and Patzek, 2005).

The EYR of potential sources when compared with current sources provides a relative relationship for evaluation of greenhouse gas emissions. For instance if we assume that ethanol with

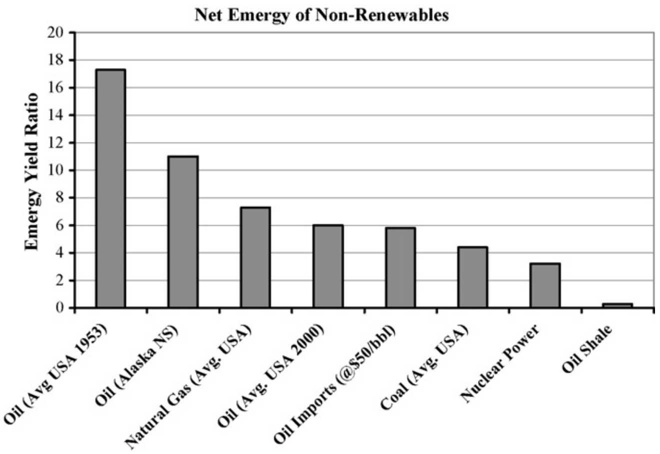

Fig. 7. Emergy Yield Ratios for conventional non-renewable energy sources. Data are from various analyses of individual processes (after Odum, 1996).

an EYR of 2–1 is used to replace fossil fuels having yields of 8–1, the ethanol is actually using energy at four times the rate, and increasing greenhouse gas emissions over the burning of the fossil fuel.

2.3. *Aggregate net emergy of USA economy*

Measuring the net emergy contributions of the energy sources driving an economy as a whole is difficult, if not impossible to do because of the many different sources, technologies, geographic locations, etc. of each individual supply train. While it is not difficult to quantify the total emergy input, it is next to impossible to estimate the emergy costs of obtaining it from each of these processes. One approach is to use the average mix of energy sources (oil, natural gas, hydropower, nuclear, etc.) and calculate a weighted average for the economy as a whole based on an average EYR for each source. The net contribution of a source is a more realistic view of a source's potential effect in increasing an economy's output. Fig. 9a is the aggregate weighted EYR for the USA economy showing an overall decline of 38% since 1950 (11/1 to 6.8/1). With time, the net contribution of energy sources to the USA economy has been declining so that, currently, the effect of non-renewable emergy input is reduced. The graph in Fig. 9b shows the difference between the gross emergy input and the aggregate net emergy input to the USA economy. Much like adjustments for inflation used to discuss monetary expenditures in constant dollars, adjusting for changes in net emergy may provide better insight into the actual contributions energy sources can contribute to economic production.

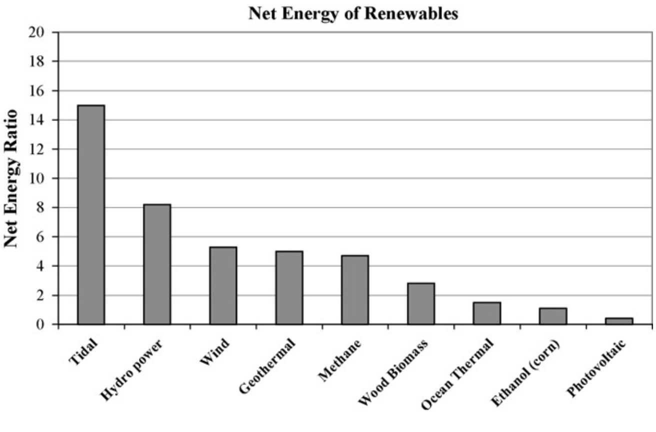

Fig. 8. Emergy Yield Ratios for so-called renewable energy sources. Data are from various analyses of individual processes (after Odum, 1996).

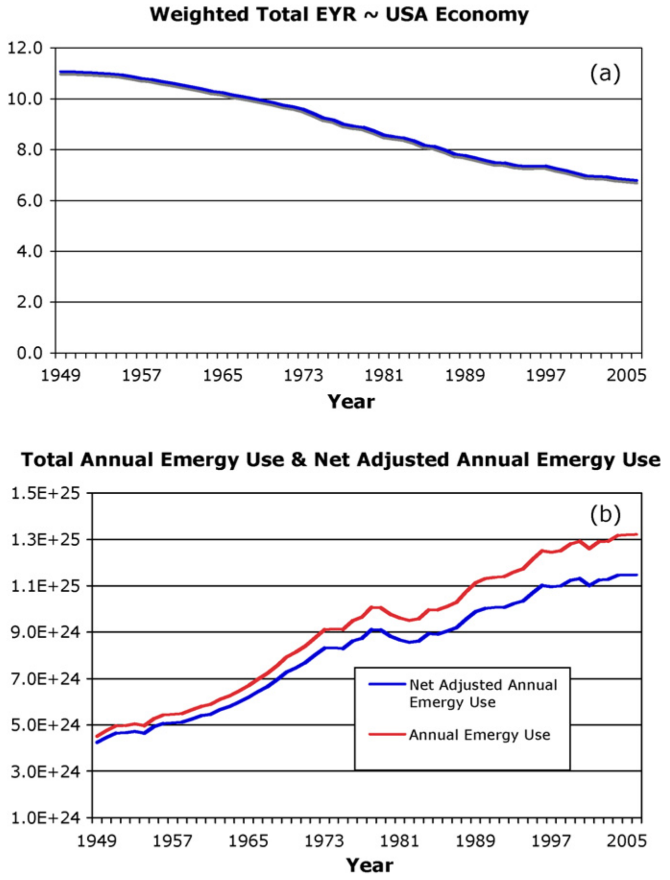

Fig. 9. (a) The change in Emergy Yield Ratio from 1949 to 2006 for main driving energies of the USA economy. Assumptions to create the graph are as follows: EYR of coal began at 18/1 and declined at a rate of 3.8% per year to end in 2006 at 7.8/1. EYR of natural gas began at 9/1 and declined at a rate of 5.1% per year to end in 2006 at 6.1/1. EYR of petroleum began at 18/1 and declined at a rate of 11% per year ending in 2006 at 7.73/1. The EYR of nuclear has remained constant at 4.6/1. Hydroelectric has remained constant at 10/1. The EYR for geothermal began in 1960 with an EYR of 2.66/1 and increase at a rate of 6% per year. Solar PV system began showing input to the US economy in 1990 with any EYR of 1.0 and has increased by 3.0% per year since then. Wind energy began inputting to the US economy in 1999 with an EYR of 8.0/1 and increased at a rate of 8.0% per year from that time, ending in 2006 at 8.6/1. The EYR of biomass in 1949 was estimated as 2.0/1 and has increased at a rate of 3.2% per year to end at a rate of 3.82/1 in 2006. (b) Total emergy use in the USA economy and the net adjusted annual emergy use. The difference is 13.3%. Net adjusted emergy use was calculated based on the change in EYR of energy sources given in (a).

3. Sustainability: understanding energetic, economic, and environmental constraints

Using data from a variety of sources, Sweeney et al. (2006) have assembled a database of inputs and outputs of materials and energy for 141 countries. The database represents the most comprehensive list of countries and their emergy flows available. They have published a detailed description of the database (Sweeney et al., 2006) and the national database calculator can be found at http://cep.ees.ufl.edu/. These data were used to evaluate national emergy use, for all countries and then to calculate the intensities and efficiencies that follow.

3.1. *Useful empower and national gross emergy product*

In engineering applications, power output is the amount of work done or energy transferred per unit of time. To the extent that resources, goods and services can be expressed as energy, then

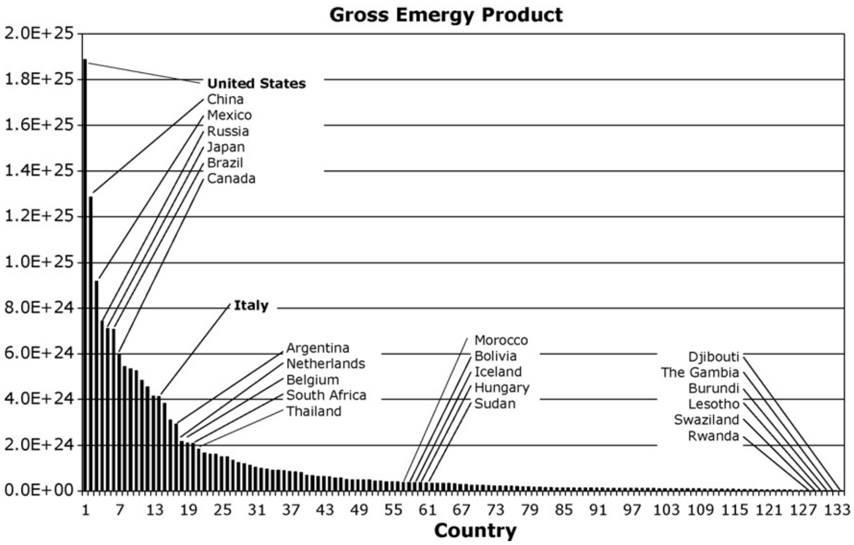

Fig. 10. Total emergy use or Gross Emergy Product (GemP) of national economies.

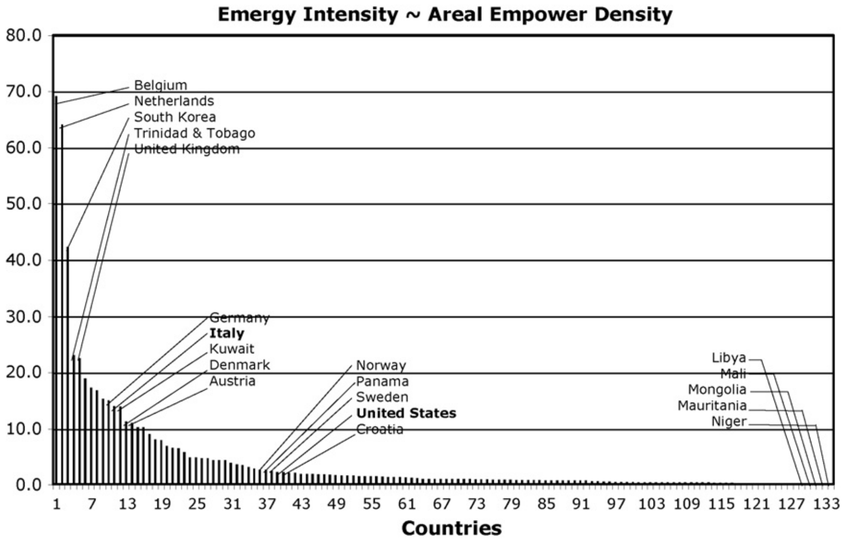

Fig. 11. Emergy intensity of national economies measured as areal empower intensity (sej year^{-1} m^{-2}). Areal empower intensity is the sum of annual renewable and non-renewable emergy use divided by area of the country.

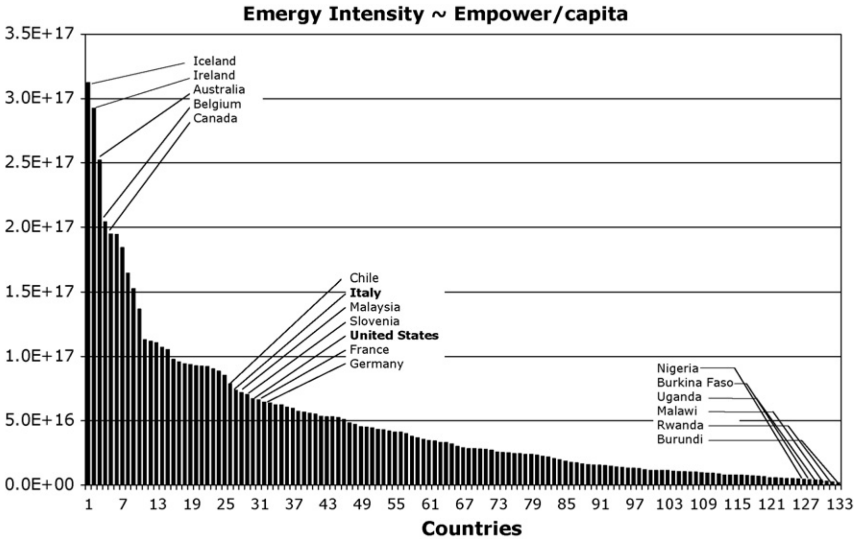

Fig. 12. Emergy intensity of national economies measured as total empower per capita (sej year^{-1} capita^{-1}). Total empower is the sum of annual renewable and non-renewable emergy use.

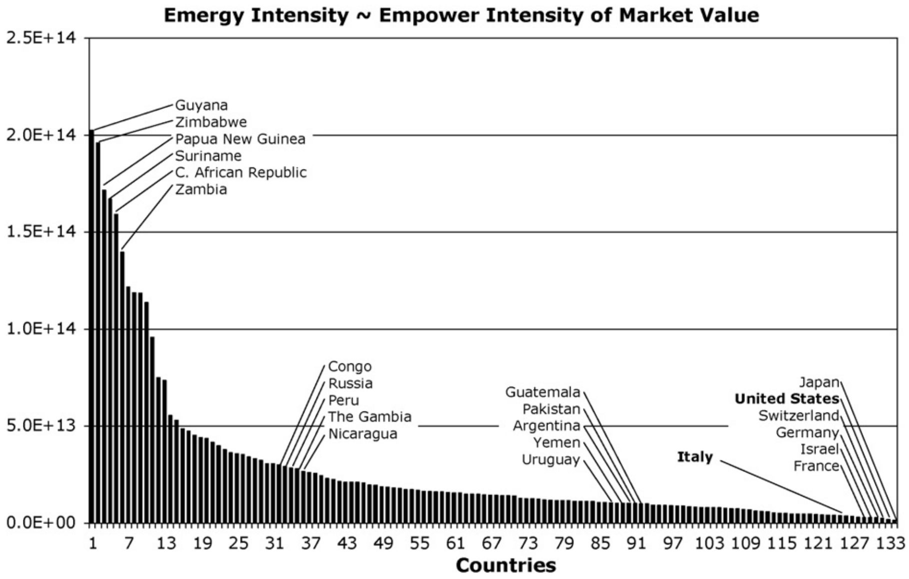

Fig. 13. A index of national emergy intensity, Empower Intensity of Market Value (EIMV) is the ratio of total annual empower (GemP) to Gross Domestic Product (GDP).

the concept of useful power can be extended to the outputs of economies and can include these more commonplace products of work processes. So we suggest the following definition for useful power in the context of national economies: useful power is the output from any process per unit time that can be applied to new endeavors. Odum (1996) defined empower as the emergy flow per unit time. Thus useful empower is the emergy of the output of any process per unit time which can be used in other processes. When the useful empower if derived for an entire country we have suggested that it is equivalent to the economic concept of Gross Product, thus we have suggested the term Gross Emergy Product (GEmP).

The graph in Fig. 10 shows the spectrum of nations arranged by their GEmP. While there are no major surprises (i.e. the USA has the highest GEmP followed by China), the fact that Mexico ranks third (driven primarily by imports) is somewhat surprising. However, Mexico is a renewable resource rich country having coastlines on two oceans which may account for its high GEmP.

3.2. *Emergy intensities of nations*

As defined, emergy intensities can be expressed either on an areal basis, a per capita basis, or a monetary basis. The following metrics for national economies illustrate some interesting consequences of emergy use by national economies.

Fig. 11 is a graph of Areal Empower Intensity showing countries with large flows of renewable emergy tend to dominate the high empower intensity end of the spectrum, while the industrialized countries tend to group in the mid range of the spectrum. Generally, countries with small footprints and either large geopotential (mountainous) or large coastlines and continental shelf areas (which translate into very high renewable emergy intensity per unit area of footprint) have the highest emergy intensities. At the other end of the spectrum, countries with small flows of renewable and non-renewable emergy use dominate.

Fig. 12 shows another measure of emergy intensity for nations, that of GEmP per capita. GEmP per capita is an index of well-being

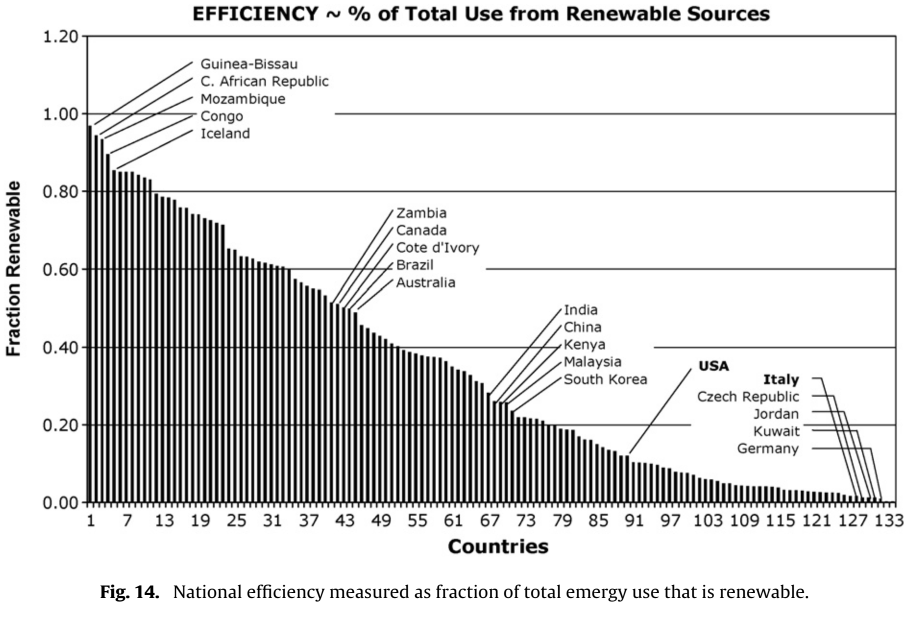

Fig. 14. National efficiency measured as fraction of total emergy use that is renewable.

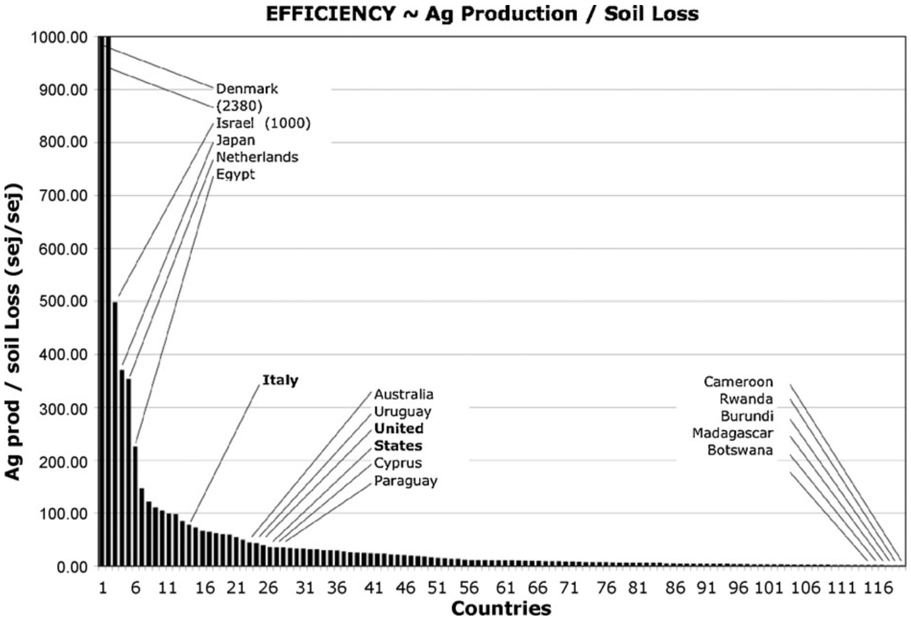

Fig. 15. National efficiency measured as the ratio of emergy value of agriculture production to the emergy value of soil loss.

of populations. In some cases total emergy use may be derived mainly from renewable sources (see Fig. 14 %renewable) and in others from non-renewable sources. In Fig. 12 the countries with highest empower per capita are countries that have large area, relatively large non-renewable flows, and relatively small population densities. Countries with few indigenous non-renewable resources and little renewable empower occupy the lower end of the spectrum. The industrialized nations tend to dominate the mid ranges of empower per capita.

The emergy intensity of market value of a national economy relates GEmP to dollars of GDP. Shown in Fig. 13 is the spectrum of nations arranged by the Empower Intensity of Market Value (EIMV) of their economies. At first glance this may seem counter to what is often suggested in the literature that GDP is related to energy throughput and therefore higher energy use results in higher GDP. While this is true, when expressed as a ratio, of GEmP to GDP the most industrialized nations have the lowest ratios, suggesting that it takes less emergy per unit of GDP generated in developed economies versus undeveloped economies. On the other hand and probably more important is the fact that countries with the highest ratios have very small GDPs and are often countries which supply raw resources to world markets instead of developing industrial infra-structure within.

In the previous examples we see a spectrum of intensities that appears sometimes counter intuitive. The most industrialized nations are not the most intense whether expressed as spatial intensity or on a per capita basis, and the economies with highest emergy per dollar of GDP are some of the least developed nations.

3.3. Indices of national economic efficiency

One measure of national efficiency is the percent of GEmP that is from renewable sources. The graph in Fig. 14 arranges the countries in the emergy database according to Percent Renewable. Economies

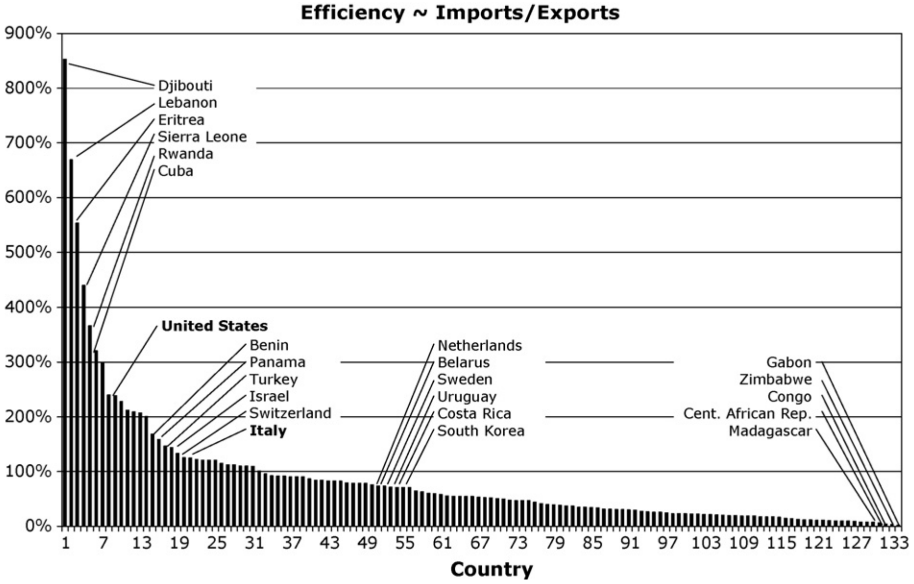

Fig. 16. National efficiency measured as the ratio of emergy in imports to the emergy of exports.

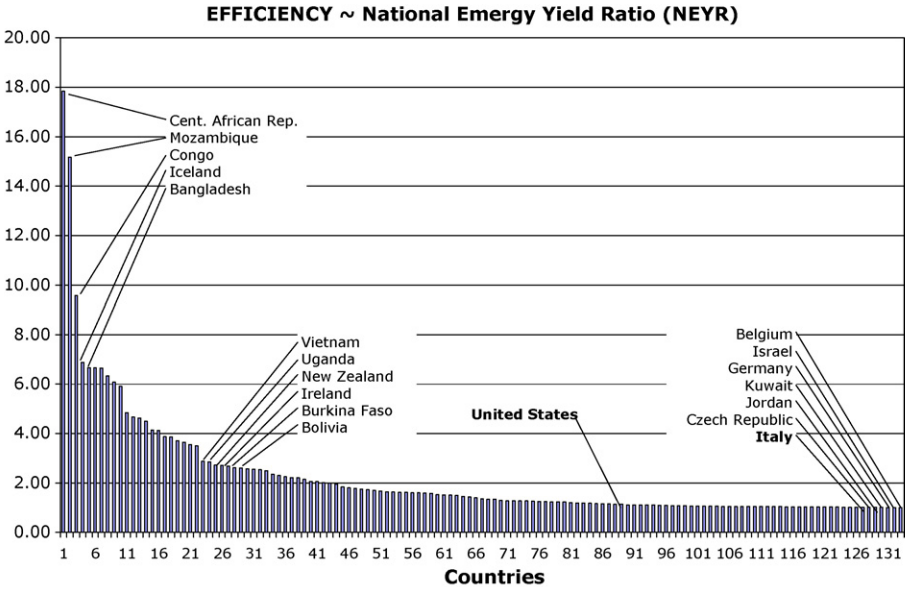

Fig. 17. National Emergy Yield Ratio (NEYR) for countries. NEYR is calculated as the total emergy use (GemP) divided by the total non-renewable emergy use, including imports.

having relatively small non-renewable empower dominate the left side of the graph. Generally, these countries have considerable difficulties providing for their populations. While countries that have the lowest percent renewable are considered by many as the most wealthy nations on the planet. Countries mid way between the two extremes present interesting characteristics. Canada and Australia, for instance, with large relatively sparsely populated interiors have nearly 50% of their total empower from renewable sources.

Soil erosion is a significant problem world wide, but appears to be far more serious in undeveloped and developing economies than in developed ones. The graph in Fig. 15 arranges the countries in the emergy database according to a ratio of agricultural production to soil loss (emergy value of agricultural production to emergy in soils eroded annually). Soil loss is expressed in emergy terms in the database. Generally, developed economies have very high agricultural yields per unit of soil loss. When expressed as percent of GemP, many undeveloped countries are experiencing soil loss rates that equal 10% to as high as 32% of their GEmP. While an avoidable emergy loss, the data suggest that developed countries have much better prospects in achieving low erosion rates, which may be enhanced by their ability to apply higher technology and information that is afforded by their higher share of the worlds non-renewable resources.

The ratio of emergy in imports to the emergy of exports is a measure of trade efficiency. That is to say, since imports are purchased with income from exports, it is a measure of the emergy in imports that can be "purchased" with the emergy sold. If national economies import raw resources and export finished products, then the ratio is higher since dollar for dollar the emergy in finished products is lower than in raw resources. The graph in Fig. 16 arranges the countries of the emergy database according to their trade efficiency. Undeveloped countries, with little or no resource base, import large quantities of emergy while exporting far less emergy, thus they have efficiencies of greater than 300%. At the other extreme, coun-

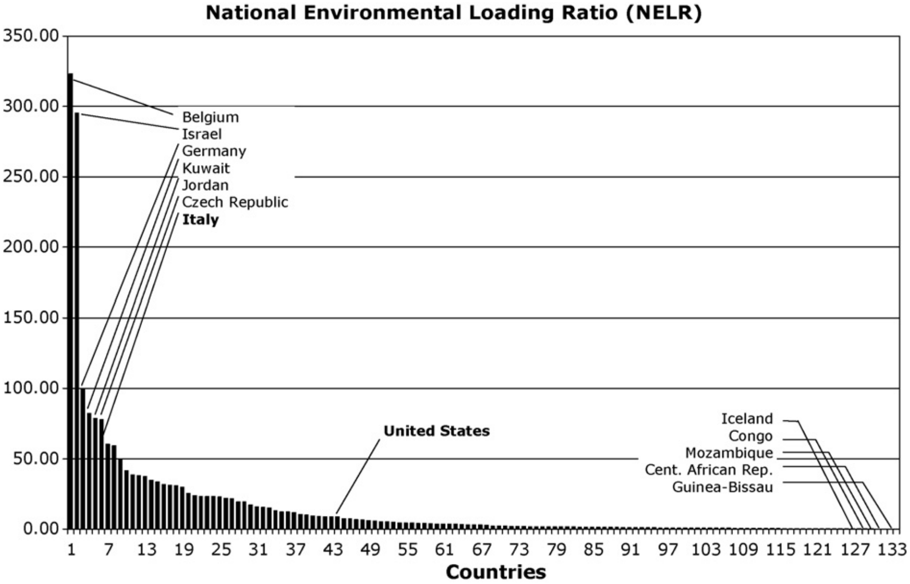

Fig. 18. National Environmental Loading Ratio. The NELR is calculated as the total non-renewable emergy use (indigenous plus imports) divided by the renewable emergy use.

tries that export large quantities of raw resources have very low efficiencies. Developing countries and some developed economies generally have efficiencies at or below 100%, trading emergy with little or no advantage.

A fourth index of efficiency is the National Emergy Yield Ratio (NEYR) defined as GEmP/non-renewable emergy use from indigenous sources. The graph in Fig. 17 arranges the countries in the emergy database by their NEYR. Countries that possess modest non-renewable resources and have relatively small economies tend to have highest NEYRs while countries with modest non-renewable resources and relatively large economies have the lowest NEYRs. Most industrialized nations fall below 2/1.

4. Environmental efficacy: minimizing environmental load

Environmental efficacy is the power to produce the desired result as it relates to a positive outcome for environment. It is the opposite of ineffectiveness. We use the term here to mean the opposite of environmental impact. The desired outcome of economies of humanity and nature should be beneficial to both environment and humanity. The environment provides free necessary inputs (sometimes on a renewable basis) to all production systems and acts as a sink for by-products from these processes.

Environmental loading results from both of these contributions of services. Environmental loading is the concept that once an environmental service is used by a process, it is not available for another process. Environmental services can be thought of as environmental support, and we use these terms inter-changeably. In the most general case, the environment has a renewable capacity to support economic processes and human endeavors but in so doing this capacity is used or consumed. If a process consumes all the renewable support functions within a region, then other processes cannot be added to the support base in the same time. Thus there is a carrying capacity to economic development. Renewable support that is provided by the environment is a load on the environment much like the load on an electrical circuit. Once all available power is consumed, additional loads cannot be added to the circuit without causing an overload.

The free services provided by the environment in absorbing and recycling by-products are of fundamental importance to a sustainable production pattern. They are seldom accounted for because the environment provides the service free of charge. . .until such time as the environment becomes overloaded. Once overloaded and the free services from the environment must be replaced by technology, then the value of the lost service can be captured as the price for replacing it. In emergy terms, at the scale of a country or region, the measure of environmental services is the emergy required to make them and is equal to the renewable resource base of the nation or region.

National Environmental Loading Ratio (NELR) – The ratio of non-renewable and imported emergy use to renewable emergy use. It is an indicator of the pressure on the environment and can be considered a measure of ecosystem stress due to overall economic activity. Fig. 18 arranges the countries of the emergy database by their NELR. Smallest countries with highest development intensities have the highest environmental loads. Large land areas and/or area of continental shelf equates to a larger area to absorb wastes and provide other environmental services.

5. Energetic, economic, and environmental constraints on sustainability

5.1. Sustainability constraints

Sustainability has been defined in many ways since its introduction as “sustainable development” in the *Brundtland Report* (http://www.un-documents.net/wced-ocf.htm). There may be as many definitions of sustainability as there are individuals working on defining it. They all have in common several things including: a belief that economy, environment and society are interconnected, that there are limits that humanity must live within, and that there should be a more equitable distribution of resources and opportunities (not only for present but future generations). In this paper we have no qualms with definitions, all of them serve to focus attention and inform debate on humanity’s place in the biosphere and the consequences of continued growth in numbers and consumption of resources.

In this paper we have peered into the resource base of society, seeking answers to the following questions: Is sustainability obtainable? and if so, how and at what cost (environmental) might we obtain it? To answer these questions we looked at various quantitative measures of energetic, economic, and environmental constraints. What we found is mixed and not easily deciphered individually, but taken collectively they paint a most interesting view of the future and potentials for a sustainable pattern of humans and environment.

5.2. Implications of net energy

Emergy yields of so-called renewables are relatively low. Those that have net emergy equal to the more concentrated fossil fuels, are relatively scarce and only exist in limited areas of the globe (wind, tide, hydroelectricity) and cannot supply needed energy at quantities sufficient to replace fossil fuels. The biomass energies all have low EYRs as well. To supply quantities of energy necessary for our modern societies would require more arable land than we currently have under cultivation for food. Moving toward biomass as an energy source will necessitate trade offs between food and energy, that is to say, feeding the world or driving to work. Turning to biomass will increase carbon emissions as lower EYRs equate to higher emergy through put for the same output.

While there is evidence suggesting the non-renewable resource base of economies may be declining, our analysis provides strong evidence that the net energy of these resources is also declining. Declining supplies coupled with declining net energies means that available energy, usable by society, will decline even faster. In other words it will take more energy to generate energy. . .with more emissions and greater environmental destruction for the same amount of useful power. This does not bode well for a more sustainable future. What does it take to get out of this trap?. . .using considerably less energy.

5.3. Implications of emergy intensity

The measures of emergy intensity of national economies, when taken together, suggests that developed economies have some of the highest areal empower intensity and emergy per capita, not surprising. What is surprising at first appearance is the fact that some of the least developed countries in the world have the highest Empower Intensity of Market Values (EIMV). However, as we have pointed out previously (Brown, 2003) the higher the EIMV, the more vulnerable an economy is to resource imperialism by developed economies, who all have lower EIMVs. In other words currencies from developed economies have greater buying power in undeveloped economies (measured as the ratios of the EIMVs), thus the continuous movement of capital investment from developed economies to undeveloped ones supports continued export of resources to the north and west.

Once again, the solutions are to reduce total emergy use in developed economies. Reducing empower per capita and per unit area, means reducing total emergy use. This will have the effect of putting the breaks on the economic engine reducing GDP, slowing the economy. The competitive stance of the economy which does this will decline globally unless all the developed economies agree to decrease total resource consumption equally. In effect this may have been the result of the Kyoto Protocol, but of course unless all the major developed economies sign on, it will falter as economies that do sign may see their competitive advantage and their economy decline.

5.4. *Implications of energetic efficiency*

Some suggest the road to sustainability is paved with increases in efficiency; that we can go a long way toward becoming more sustainable by becoming more efficient. Admittedly there is much room for improvement. However, when we take a number of emergy efficiency measures in aggregate, what appears suggests that increases in efficiency will not solve the sustainability crisis and may come at a relatively high cost. The percent of total resource use that is derived from renewable sources is calculated based on the total renewable input to the country's area. It cannot be increased since it represents the total input, thus to increase the percent renewable and thereby the sustainability of an economy requires either confiscating land elsewhere or reducing non-renewable emergy use. Economies with the highest GDP/GEmP ratios are the developed nations, those with the highest emergy use. It requires extremely large flows of emergy per year to maintain large GDPs. Increases in this measure of efficiency mean increases in emergy throughput in the economy. It is not a matter of increasing economic efficiency by generating more economic product per unit of emergy use as it appears that increases in the ratio come from very large throughput.

Agriculture production in developed economies requires large flows of emergy in the form of fuels, fertilizers and equipment as well as human inputs. The result is extremely high outputs per unit of land. Where agriculture must rely on fewer emergy inputs, the area of land must be greater to supply the same level of yield since yields are lower per unit of land. As a result soil erosion rates are highest in the undeveloped countries of the world. Becoming more efficient regarding the amount of agriculture output per unit of soil eroded apparently means that countries must increase their GEmP for those countries with the highest agricultural/soil efficiencies are those with some of the highest GEmPs.

Trade sustainability, while a complex issue, might be simplified by exploring the relationship between emergy in imports versus the emergy in exports. The idea being sustainable trade policy should strive to balance the emergy in imports to be equal to the emergy in exports. So as a measure of efficiency the higher the ratio of emergy in imports to emergy in exports the more the economy that experiences this high ratio is taking advantage of its trading partners. Many developed economies have import/export efficiencies of 200%. To increase this efficiency apparently means importing more raw resources and exporting finished products. Increases in emergy trade efficiency for the vast majority of countries with less than 1 to 1 can only mean a decrease in emergy trade efficiencies for the 31 countries that have efficiencies greater than 100%.

The National Emergy Yield Ratio (NEYR) is an efficiency measure of how well indigenous resources are used. The higher the ratio the more effective an economy is in "investing" their non-renewable emergy. Of course countries with few indigenous non-renewables may have very high ratios, so this efficiency measure alone may not tell the entire story. The most efficient economies as measured by NEYR are the least developed which translates to either not having indigenous resources or exporting them and not using them within the economy. The majority of developed nations have ratios less than 2–1 suggesting that they are using considerable amounts of their indigenous resources.

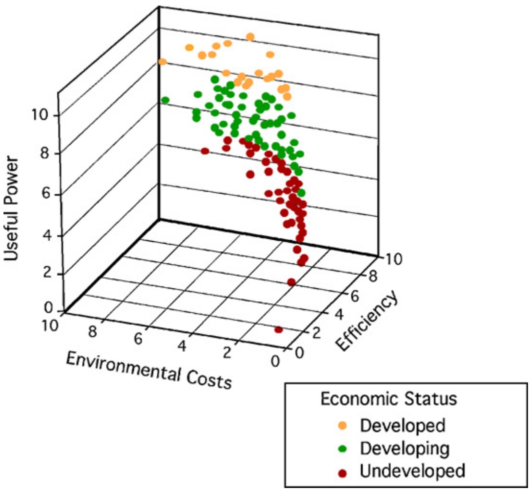

Fig. 19. The constraint space of environmental cost (normalized ELR) vs. efficiency (normalized NEYR) vs. total useful power (normalized GEmP). As development status increases nations increase efficiency but at increasing environmental costs.

The graph in Fig. 19 uses the data in the global emergy database to generate the current constraint space occupied by nations. The axes are normalized to make comparison easier. Environmental costs equates to the Environmental Loading Ratio, Efficiency is a normalized National Emergy Yield Ratio, and total power is a normalized GEmP. Countries have been colored to highlight three development conditions, highly developed industrialized nations, moderately developed nations and developing nations. The relationships shown provide another look at the constraint space that surrounds likely futures. Generally lower total power means lower efficiencies, and low to moderate environmental degradation, As development status increases, efficiencies increase but so do the environmental impacts associated with increases in GEmP.

5.5. *An emergy measure of sustainability*

Beginning in 1997, we suggested an Emergy Sustainability Index (ESI).[2] We now refer to this index as EmSI.

Emergy Sustainability Index (EmSI) – The EmSI for a nation is the ratio of the its NEYR to its ELR. It is an index that accounts for yield, renewability, and environmental load and is the incremental emergy yield compared to the environmental load.

The EmSI is a measure of an economy's long-term global position relative to others. Low EmSI's are indicative of economies that import a large fraction of their GEmP and consume a relatively large percentage of total emergy in the form of non-renewable emergy. We suggest that sustainability of an economy is a function of renewable emergy flows, the extent to which it depends on imports, and its load on the local environment. The EmSI, provides a multi-dimensional measure of long-term sustainability. The higher this index the more an economy relies on locally renewable energy sources *and* minimizes imports and environmental load.

Fig. 20 arranges the countries of the emergy database by their EmSI. The most intensely developed countries have lowest EmSIs. Industrialized nations, for the most part, all fall below 1.0. Countries

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[2] In earlier publications, we used ESI for Emergy Sustainability Index (Brown and Ulgiati, 1997). Recently however we realized that the joint initiative of the Yale Center for Environmental Law and Policy (YCELP) and the Center for International Earth Science Information Network (CIESIN) of Columbia University, in collaboration with the World Economic Forum and the Directorate-General Joint Research Centre (European Commission) also constructed an Environmental Sustainability Index (ESI), a composite index tracking 21 elements of environmental sustainability. To avoid confusion, we now use EmSI to refer to the emergy sustainability index.

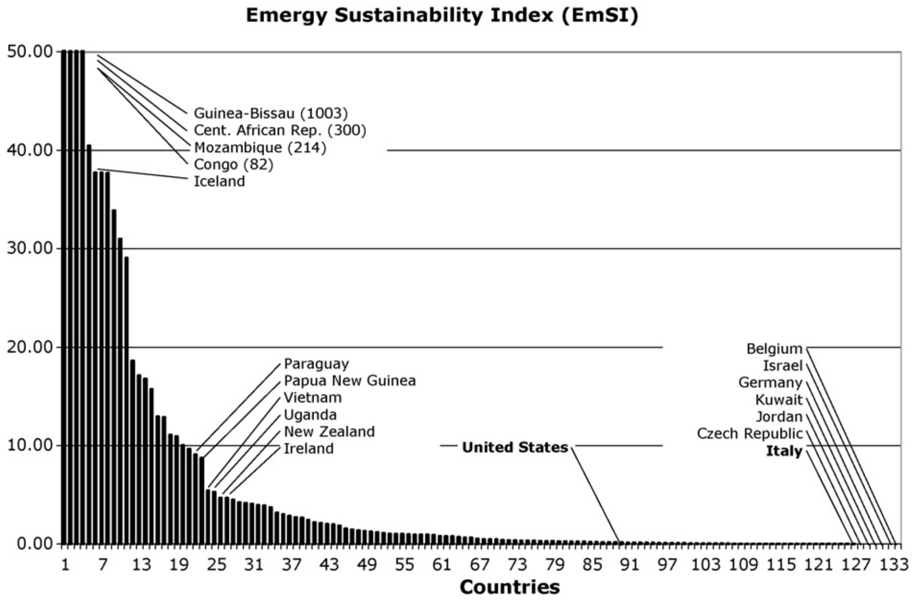

Fig. 20. Emergy Sustainability Index (EmSI) for countries. The EmSI is calculated as the National Emergy Yield Ratio (NEYR) divided by the Environmental Loading Ratio (ELR).

with moderate levels of industrialization and large natural renewable emergy bases have EmSIs that range from 20/1 to 50/1, while undeveloped countries with very small economies have the highest EmSIs.

5.6. *Sustainability and carrying capacity*

The concept of carrying capacity for human use of the biosphere is important since limits to the biosphere's ability to sustain life, absorb and recycle wastes, and provide resource inputs are becoming more apparent. There has been renewed interest in understanding the relationship between human-dominated systems and environmental support areas. We have proposed methods, using emergy analysis techniques, for evaluating carrying capacity of economic developments (Brown and Ulgiati, 2001). Folke et al. (1997) estimated "appropriated ecosystem areas" by cities in the Baltic area for resource consumption and waste assimilation. Wakernagel and Rees (1995) have evaluated requirements for land to provide resources for urban areas and coined the term "ecological footprint." Concern over increased volumes of CO_2 emissions resulting from human consumption of resources has prompted studies of forest area required to sequester CO_2 (see for instance Winjum et al., 1992).

The newer term, sustainability seems to subsume carrying capacity by suggesting that the long-term greater good of humanity is best maximized by minimizing environmental impacts and maximizing useful work. There are limits to environments for providing services and resources and there are limits for environments absorbing wastes. Thus long-term sustainability is in many ways long-term carrying capacity. It is quite apparent to us that carrying capacity of the global environment for humanity has been exceed and is only sustained through large inputs of non-renewable resources. Ultimately the carrying capacity of the globe for humanity is set by the annual emergy income of the planet from renewable sources. In previous work we estimated that the total renewable input to the globe was 15.83 E24 sej/year (Brown and Ulgiati, 2004). If the emergy standard of living is taken as 2.4 E 16 sej/capita/year (average global per capita emergy use), then the carrying capacity of the earth's biosphere is about 670 million people or about 10% of the current population. This of course suggests that populations would live solely on their renewable income thus population densities would be sparse and they would rely on gathering emergy from relatively dilute renewable sources.

6. Summary: the path toward a sustainable future

The future holds endless possibilities, each obtainable by numerous paths. Yet we humans have very mixed signals regarding which endpoint is ultimately the right one and which pathway is the most appropriate and desirable to get there. There is no question that humanity's numbers are increasing worldwide, and that demand for resources is increasing even faster. A serious question that we must address while we contemplate a sustainable future is. . .How do we provide for an increasing global population and geometric increases in resource consumption? What follows are potential solutions and arguments for or against them.

6.1. *Shift to renewable energy*

Many suggest that humanity should shift the economy's driving energies from fossil fuels to more renewable forms of energy such as solar, wind, tides, or biomass. Unfortunately, each of these renewable sources is less concentrated than fossil fuels and of lower quality. To utilize them for the complex tasks required in a modern info-industrial economy requires that they be upgraded to a quality commensurate with the economy's requirements. Yet, the net emergy from these renewable sources that would be available to society suffers in the upgrading process. Our analysis of the net emergy from renewables suggests we cannot shift to renewables and ever hope to provide the energy required by current demand, much less that projected for an increasing population and consumer driven demand. The renewable environmental energies like wind, geothermal, or tide only occur at intensities sufficient to provide net energy in very limited areas of the planet and thus their total contribution will not replace much of global energy needs. Biomass energies require large areas of arable land and huge quantities of water which will ultimately contribute to increased competition for food and fiber. In short the renewables do not represent the panacea many suggest.

Cleveland (2007) has outlined significant constraints that result from difference in the energy quality of the renewable energies from fossil fuel energies, including: gravimetric and volumetric energy density, power density, emissions, cost and efficiency of conversion, financial risk, amenability to storage, risk to human health, spatial distribution, intermittency, and difficulties associated with transport. These constraints suggest that renewable alternative energy sources are inferior to fossil fuels in their dependability, flexibility, and net yields and they are not likely to supplant fossil fuels as the chief source of power for economies of the globe.

6.2. *Reliance on traditional forms of energy*

Best estimates of storages of conventional fossil fuels suggest that new discoveries of petroleum may have peaked and that yields from the main oil fields are in decline, resulting in a peak in supply and future decline. Coal is another matter, early estimates by Hubbert (1971) suggested that there may be sufficient global coal storages to supply 300 years at current (1970s) demand. Yet today the World Coal Institute (2007) suggests that at current production levels proven coal reserves will last 147 years. The US Energy Information Administration, in their IEO2007 analysis suggest world coal consumption will increase by 74% from 2004 to 2030 and coal's share of world energy consumption will increase from 26% in 2004 to 28% in 2030 by which time world consumption will be nearly double that of today. These estimates do not take into account net emergy, nor the fact that coal is lower quality and to upgrade to liquid fuels or other versatile forms, will lower its net yields even further. The result may shrink these estimates to 100 years or less.

In all, conventional energy sources will be relied on heavily to fuel at least the immediate future. The potential for the release of ever increasing quantities of pollutants into the global environment is a significant future scenario. Increased demand for energy coupled with lower net yields of sources equals geometric increases in green house gas emissions, other pollutants, environmental degradation, and consequent decreases in human health and long-term sustainability.

6.3. *Technological fix: increase efficiency*

Increases in efficiency of conversion of energy and resources in productive processes of economies come at a cost. Our analysis of several measures of national efficiency suggests that the most efficient countries are those at the extremes of the GEmP gradient. They are either very emergy intensive, or they are without much emergy through put. Admittedly our indices are simplistic, but taken together they represent a multi-dimensional look at how emergy interacts with economies. Disregarding the poorest countries, as the amount of emergy use in an economy increases, national measures of efficiency increase, whether its a measure of agricultural production per unit of soil erosion, or the amount of emergy required to generate a unit of GDP.

Increases in efficiency are a two edged sword. Many suggest that increases in efficiency may actually increase energy use (Jevons Paradox or Rebound Effect) as the increase results in lower costs and higher demands. In addition, efficiency costs energy. The technology and information necessary for increases in efficiency do not come cheaply. Industrialized economies invest considerable amounts of energy and resources in higher education, research, and development. New technologies that may increase efficiency frequently result in increased energy use, not energy savings.

6.4. *Technological fix: a new as yet unknown energy source*

Finally, it is often suggested that with time and ingenuity a new, as yet unheard of technology will provide unlimited amounts of energy. Fusion is often suggested as a possibility, or some other source not yet imagined. This technological optimism underlies much of current societal opinion on the subject of the future. After all, advances in technology over the past 50 years have definitely changed every aspect of modern economies and the lives that depend on them. What is to stop yet more innovation that will solve the energy crises forever?

The answer is simple. The advances experienced by humanity have required enormous quantities of energy to pull them off. Today humans enjoy unprecedented comfort, mobility, and productivity that flows directly from the vast quantities of energy consumed. With each increase in technology from oxen to waterwheels, to wood, to coal to oil, has come higher power available to humans and increased productivity. At the same time the energy required to maintain these new technologies has also increased. In industrialized economies today, emergy use per capita is almost 1000 times the emergy per capita of people living 100 years ago. Technological improvements go hand in hand with increased energy demand.

We are convinced that humans will strive for any number of potential solutions to the energy dilemma. Money and energy and human ingenuity will be invested in the hopes of finding a new energy source or a more efficient process of utilizing existing sources. If it is found it means more of the same, more growth of demand, more consumption, greater amounts of waste, and increased environmental load. The growth of wastes and environmental load if dealt with will decrease available energy that can be directed toward production of goods, services, and infra-structure for humanity, so that the end my not be much improved quality of life or human welfare.

6.5. *The lower energy future*

With global population growth at about 2% per year and demand for resources increasing even faster, most would agree that such geometric increases cannot continue forever. . .that at some time it will be necessary to curtail these growth rates and develop a steady state pattern of existence. The question then, is. . .When should humanity rethink its current fascination with growth and development and instead think sustainable steady state? Is it appropriate now? If it is appropriate now, then how do we accomplish a sustainable steady state pattern?

In their book The *Prosperous Way Down*, Odum and Odum (2001) have outlined principles and policies for transition from our current growth ethic that presupposes that we can grow our way out of the any problem to an ethic that is more sustainable in the long run. They suggest that the only solution is contraction of economies, declines in overall power and productivity, and a shrinking consumerism. To avoid calamity, and to increase the probability of human survival, they suggest that we must remain prosperous during the decent, and to do this we humans will need to reduce populations at the same rate as the annual energy becomes less available. Money supplies should likewise be reduced to avoid hyper-inflation.

The earth cannot tolerate continued growth in economies, populations, and the consumerism that they foster. While the energy, economic and environmental constraints that operate at all scales may limit future growth (which may be a good thing), instead of a planned descent we may face abrupt change. It remains to be seen if humans can foresee it, adjust in time, and weather the transition. What is desperately needed is a new belief to replace our worn out growth ethic. . .a belief that a steady state, decentralized civilization can be a better place to live and that in the words of architect Ludwig Mies van der Rohe, *"Less is More*".

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