Environ Dev Sustain (2008) 10:787–825
DOI 10.1007/s10668-007-9085-4

Will progress in science and technology avert or accelerate global collapse? A critical analysis and policy recommendations

Michael H. Huesemann · Joyce A. Huesemann

Received: 24 May 2006 / Accepted: 24 January 2007 / Published online: 21 June 2007

Abstract Industrial society will move towards collapse if its total environmental impact (I), expressed either in terms of energy and materials use or in terms of pollution, increases with time, i.e., $dI/dt > 0$. The traditional interpretation of the $I = PAT$ equation reflects the optimistic belief that technological innovation, particularly improvements in eco-efficiency, will significantly reduce the technology (T) factor, and thereby result in a corresponding decline in impact (I). Unfortunately, this interpretation of the $I = PAT$ equation ignores the effects of technological change on the other two factors: population (P) and per capita affluence (A). A more heuristic formulation of this equation is $I = P(T)\cdot A(T)\cdot T$ in which the dependence of P and A on T is apparent. From historical evidence, it is clear that technological revolutions (tool-making, agricultural, and industrial) have been the primary driving forces behind successive population explosions, and that modern communication and transportation technologies have been employed to transform a large proportion of the world's inhabitants into consumers of material- and energy-intensive products and services. In addition, factor analysis from neoclassical growth theory and the rebound effect provide evidence that science and technology have played a key role in contributing to rising living standards. While technological change has thus contributed to significant increases in both P and A, it has at the same time brought about considerable eco-efficiency improvements. Unfortunately, reductions in the T-factor have generally not been sufficiently rapid to compensate for the simultaneous increases in both P and A. As a result, total impact, in terms of energy production, mineral extraction, land-use and CO_2 emissions, has in most

---

Readers should send their comments on this paper to BhaskarNath@aol.com within 3 months of publication of this issue.

M. H. Huesemann (✉)
Marine Sciences Laboratory, Pacific Northwest National Laboratory, 1529 West Sequim Bay Road, Sequim, WA 98382, USA
e-mail: michael.huesemann@pnl.gov

J. A. Huesemann
Critical Science Institute, 998, Carlsborg, WA 98324, USA

cases increased with time, indicating that industrial society is nevertheless moving towards collapse. The belief that continued and even accelerated scientific research and technological innovation will automatically result in sustainability and avert collapse is at best mistaken. Innovations in science and technology will be necessary but alone will be insufficient for sustainability. Consequently, what is most needed are specific policies designed to decrease total impact, such as (a) halting population growth via effective population stabilization plans and better access to birth control methods, (b) reducing total matter-energy throughput and pollution by removing perverse subsidies, imposing regulations that limit waste discharges and the depletion of non-renewable resources, and implementing ecological tax reform, and (c) moving towards a steady-state economy in which per-capita affluence is stabilized at lower levels by replacing wasteful conspicuous material consumption with social alternatives known to enhance subjective well-being. While science and technology must play an important role in the implementation of these policies, none will be enacted without a fundamental change in society's dominant values of growth and exploitation. Thus, value change is the most important prerequisite for avoiding global collapse.

Keywords Collapse · Consumption · Eco-efficiency · Industrial ecology · IPAT equation · Population growth · Rebound effect · Steady-state economy · Subjective well-being · Sustainable development

1 Introduction

Most societies, including those as complex as the Roman and Mayan, have collapsed and vanished after having enjoyed long periods of prosperity (Diamond, 2005; Tainter, 1988; Wright, 2004). There is, therefore, no reason to believe that our extremely complex technological society is not also subject to collapse. Indeed, all three pre-conditions for environmental and societal collapse are present in current technological societies (Meadows, Randers, & Meadows, 2004): (i) Rapid growth in resource use and pollution, (ii) limited resource availability and waste absorption capacity, and (iii) delayed responses by decision-makers when limits have already been exceeded (''overshoot'') or soon will be. According to Meadows et al. (2004, pp. 164 &167):

> ''If the signal or response from the limit is delayed and if the environment is irreversibly eroded when overstressed, then the growing economy will overshoot its carrying capacity, degrade its resource base, and collapse. The result of overshoot and collapse is a permanently impoverished environment and a material standard of living much lower than would have been possible if the environment had never been overstressed... On the local scale, overshoot and collapse can be seen in the processes of desertification, mineral or groundwater depletion, poisoning of agricultural soils or forest lands by long-lived toxic wastes, and extinction of species. .... On the global scale, overshoot and collapse could mean the breakdown of the great supporting cycles of nature that regulate climate, purify air and water, regenerate biomass, preserve biodiversity, and turn wastes into nutrients.''

Despite the warning signs of overshoot and impending collapse, most traditional (i.e., neoclassical) economists do not appear to be concerned but rather convey a sense of profound technological optimism, expressed in the belief that human ingenuity and progress in science and technology will solve all current problems and pave the way to a paradise-like technotopia (Beckerman, 1996; Simon, 1996). These may be the views of naïve neoclassical economists who are extreme techno-optimists, but many ecological economists also believe that technological change will provide solutions to serious and even persistent environmental issues such as resource constraints imposed by finite stocks of mineral and oil resources (Vollebergh & Kemfert, 2005). And with very few exceptions, most of the science and engineering literature dealing with environmental and sustainability issues conveys the implicit optimism that ''Technology will Spare the Earth'' (Ausubel, 1996). But will it?

In order to establish that technology indeed has the potential to prevent environmental and societal collapse, it must be shown that progress in science and technology will result in a reduction of total environmental impact (I), as expressed either in terms of resource use or pollution. According to the well-known IPAT equation (Chertow, 2001; Ehrlich & Holdren, 1971; Graedel & Allenby, 1995), total impact may be expressed as:

$$I = P \cdot A \cdot T \tag{1a}$$

where P is the population size [number of people, or more correctly, consumers], A is affluence [per capita GDP], and T is the impact of technology [resource use or pollution per GDP]. Note that T is inversely proportional to technological efficiency (e), i.e.,T = 1/e, see also Sect. 4.

It is generally assumed that improvements in eco-efficiency will substantially reduce the T-factor in Eq. 1a, thereby decreasing total resource use and pollution (i.e., $dI/dt < 0$), and in doing so, achieve sustainability and prevent collapse (Huesemann, 2003). Unfortunately, this interpretation of the IPAT equation ignores the effects of technological change on the other two factors, P and A. Therefore, the equation is more correctly written as:

$$I = P(T) \cdot A(T) \cdot T \tag{1b}$$

It thus becomes apparent that while technological progress will improve eco-efficiencies (i.e., will reduce T), it may at the same time increase per capita affluence and the size of the consumer population, demonstrating that the effects of technological change on total environmental impact is more complex than currently assumed. It is, therefore, the objective of this paper, using primarily historical data and other empirical evidence, to show how technological change has affected population growth, affluence, and efficiency, and whether or not, in the *aggregate*, technological innovations have reduced total impact (I). In addition, specific policy options are discussed which could accelerate the reduction of total impact, specifically by (i) reversing population growth, (ii) improving technological efficiencies in order to decrease matter-energy throughput, and (iii) promoting the transition to a steady-state economy where per capita affluence is stabilized at sustainable levels.

2 Technological progress increases the size of the consumer population

The size of the consumer population (P) is proportional to the size of the total human population (P_{tot}) multiplied by the fraction (f) of this population which consumes a particular product or service, i.e., $P = f \cdot P_{tot}$. Science and technology have contributed to a phenomenal increase in both P_{tot} and f. Throughout human history, major technological innovations have played a crucial role in promoting a series of population explosions, primarily by expanding the carrying capacity of the land and by lengthening life expectancy through medical interventions. More recently, modern technology has been instrumental in spreading the western materialistic lifestyle with the help of electronic media and highly effective transportation technologies, thereby converting an ever increasing fraction of the earth's inhabitants into consumers of material- and energy-intensive products and services.

2.1 Population explosions occur in response to technological revolutions

Human numbers increased from as small as 10,000 at approximately 130,000–150,000 years ago to over 6,600,000,000 today (Deevey, 1960; Jobling, Hurles, & Tyler-Smith, 2003). While this population increase appears to be exponential, a closer analysis shows that the expansion of human populations has actually occurred in several separate stages in response to climate changes as well as a series of technological revolutions (see Fig. 1). The invention of advanced stone tools during the Upper Paleolithic enabled hunter-gatherers to expand from their origins in Africa into Eurasia approximately 40,000–50,000 years ago with total population increasing to as much as 10 million on the eve of the agricultural revolution. The invention of agriculture c. 10,000 years ago greatly multiplied the carrying capacity of the land and involved the stabilization and expansion of the food supply. As a result, human population increased to more than 100 million by c. 2000 years ago (Deevey, 1960; Jobling et al., 2003).

The rapid and synergistic development of science and engineering that began more than 300 years ago led to a proliferation of technological inventions, most importantly the steam engine, the internal combustion engine, and the electric generator. A major effect of the industrial revolution was an enormous increase in

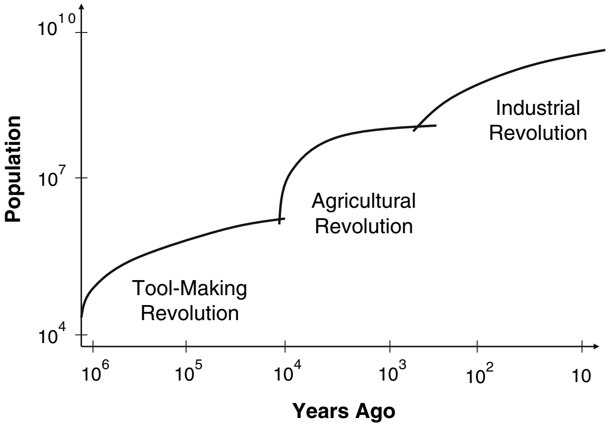


Fig. 1 Human population surges in response to three different technological revolutions. Please note logarithmic scale. Adapted from Deevey (1960)

food production brought about by the industrialization of agriculture, first through the introduction of fossil fuel powered farm machinery, which facilitated the rapid conversion of forests and prairies into farmland, and later through the increase in crop productivities through the application of fossil fuel based fertilizers, pesticides, large-scale irrigation, and genetic engineering (see, for example, Fig. 8 in Sect. 4 below showing the substantial increase in U.S. corn yields and production). Essentially, non-renewable fossil energy was substituted for land and labor. As a result of the industrial revolution in agriculture, the carrying capacity of the land has expanded at least 10-fold, with human numbers increasing from approximately 545 million 350 years ago to more than 6 billion today (Deevey, 1960).

While industrial agriculture provided the food necessary for increasing populations, progress in medical science and technology gradually lengthened life-expectancies by first reducing infant mortality and then by providing cures for degenerative diseases that occur later in life (McKeown, 1988). The average life expectancy at birth has more than doubled in Europe and the United States from only 37 years in 1820 to approximately 76 years in 1987 (Maddison, 1991, Table B6). More recently, with the development of oral contraceptives about 40 years ago, modern medicine has for the first time contributed to a decrease in population growth, primarily in developed nations with Third World nations expected to follow this pattern.

The Industrial Revolution began in Europe about 300 years ago and subsequently has spread worldwide via intensive technology transfer, initially during colonization by Europeans and more recently as part of Third World development efforts. The green revolution is one the best examples of such technology transfer. As technological development in Europe led to rapid population increases there during the 19th and 20th centuries, technology transfer to Third World nations has been primarily responsible for the current world-wide population explosion (Ehrlich and Ehrlich, 1991).

All of the three major increases in world population were based on improved access to energy. When, through technological innovation, access was gained to more energy than previously had been available, food production increased and populations grew in direct proportion[1]. As early hunter-gatherers expanded their territories, more captured solar energy in the form of additional plants and animals became available. The subsequent development of agriculture intensified the photosynthetic conversion of solar energy fluxes into food biomass with an even greater effect upon population size. The current access to fossil energy has led to increased crop productivities both in terms of land and labor, fueling the most recent and largest growth in human population.

The fact that fossil energy stocks are non-renewable and likely to be depleted in the near future[2] indicates that the current world population of more than 6 billion, much of which depends on fossil fuel inputs for food production, cannot be sustained indefinitely. With the anticipated decline in the availability of cheap fossil fuels, world agricultural production will ultimately have to revert to the more labor-intensive and less productive farming methods of earlier times. It is highly unlikely

---

[1] As Pimentel and Pimentel (1996) have shown, there is a strong correlation between global energy use and world population growth, particularly after 1700.

[2] Global production of crude oil is likely to peak within the next decade and decline thereafter (Campbell & Laherrere, 1998; Romm & Curtis, 1996).

that enough food can be provided without fossil energy inputs for the ca. 9.5 billion people that are expected by 2050 (Gaffin, 1998), given that the very stability and relatively low population density of traditional agricultural societies was determined by the dependence on the limited but steady flux of solar energy, which could never be increased but only allocated to arable acreage, pasture, and forest to provide crops, animal energy, and fuel in the desired proportions (Sieferle, 2004).

It can therefore be concluded that the very success of the Industrial Revolution has placed humans in a very precarious position: unless there are concerted efforts to voluntarily and significantly reduce the size of the human population within the next hundred years, a global population collapse is inevitable. While progress in science and technology has been a major contributor to uncontrolled population growth and has increased the risk of population collapse, medical science may provide the means to reduce population growth rates sufficiently to avert a global catastrophe, a topic discussed in more detail in the policy Sect. (6) below.

2.2 Communication and transportation technologies promote the globalization of materialistic consumer life-styles

While a global human population of more than 6 billion already poses a serious challenge to sustainable food production, many environmental problems will become significantly aggravated as the Third World adopts the energy- and material-intensive lifestyle of developed nations. As is evident from Eq. 1, the magnitude of the environmental impact depends not on the total population size per se but on the number of persons who consume particular commodities and services. Unfortunately, the relatively recent progress in transportation and communication technologies has enabled corporations to globalize markets and entice billions of people, who until recently lived relatively simple and low-impact lives, to a highly materialistic western lifestyle, which poses a serious threat to the environment.

Prior to the Industrial Revolution, transportation of goods was severely restricted by the availability of animal power and wind (Sieferle, 2004). As a result, the production and consumption of basic commodities in agricultural societies was localized and decentralized, with trade limited to a few valuable goods such as precious metals and spices. With the construction of great maritime fleets, Europeans were able to "discover" other continents and convert them into colonies. Trade and technology transfer was restricted at first by the slow speed and limited capacity of sailing ships and animal-driven carriages. However, this changed with the invention of the steam-engine which enabled transport by steamship and railroad. Later, the internal combustion engine led to an explosion during the last 100 years in transport by sea, land, and air. As a result of these technological innovations, global trade as well as technology transfer to Third World nations has increased by many orders of magnitude.

While various fossil fuel based transportation technologies have enabled corporations to provide millions of consumer products, modern communication technologies, especially the television and more recently the internet, have assisted in generating the desire for these goods. It is clear that the rapid globalization of the western materialistic lifestyle would have been impossible without the television. In fact, the primary purpose of television is to advertise products and services, with movies and news serving as entertaining fillers to keep the viewer in a receptive state of mind (Mander, 1978). Approximately 99.5% of all American homes have television sets, and 95% of the U.S. population watches television regularly, on average 4.5 hours a day. Internationally, the situation is little different from the United States, with about 80% of the global population having access to television (Cavanagh & Mander, 2002).

The intensity with which corporations use television advertising and movies to seduce unsuspecting viewers to a material and energy-intensive consumer lifestyle has been succinctly pointed out by Cavanagh and Mander (2002, p. 237):

> ‘‘In the United States, the average viewer of television sees about twenty-eight thousand commercials every year. That is twenty-eight thousand times that they are hit by extremely invasive imagery saying virtually the same thing. One may be about tooth paste, and another about cars, cosmetics, and or drugs. But the intent of each of these commercials is identical: to persuade people to view life as a nonstop stream of commodity satisfactions. Cumulatively, globally, the commercialization effect is immense’’.

Cavanagh and Mander (2002, p. 241) then summarize:

> ‘‘We have the most powerful and pervasive communications systems in history, dominated by a tiny handful of corporate people, describing how life should be lived. Is this good? Is it o.k. for billions of people to be receiving nonstop doses of powerful images and information controlled by such few sources, essentially telling them to be unhappy about their own cultures and values—how they live and who they are—to get onto the commodity treadmill, to put their trust in corporations, and to embrace a global homogenization of Western values? Will this bring a sustainable, equitable society? Many think not.’’

In conclusion, technological progress in its various forms has not only brought about an exponential increase in population size but, more recently, has been used to transform most of the world’s inhabitants into consumers of material- and energy-intensive products and services. Clearly, progress in science and technology has been a major factor in increasing the P-factor in Eq. 1, thereby escalating the risk of global population and ecological collapse. While, in principle, advances in science and technology can be used to reduce these risks, a blind faith in progress without a change in the direction of progress will not solve these most critical problems—a topic discussed in more detail later.

3 Technological progress contributes to rising affluence

In addition to producing a population explosion, the Industrial Revolution has led also to a large increase in economic output and affluence worldwide. Consider, for example, that global industrial output has risen by a factor of 100 since ca. 1750 and over the last hundred years has grown 40-fold (Gruebler, 1994). The fact that economic output grew much faster than the number of people resulted in a steep rise in per capita affluence (A). As shown in Fig. 2, per capita GDP increased on average 14-fold between 1820 and 1989 in industrialized nations (Maddison, 1991). These trends are expected to continue. According to different development scenarios published in the Third Assessment Report of the International Panel of Climate Change (Huesemann, 2006; IPCC, 2001), gross world product (GWP) is projected to

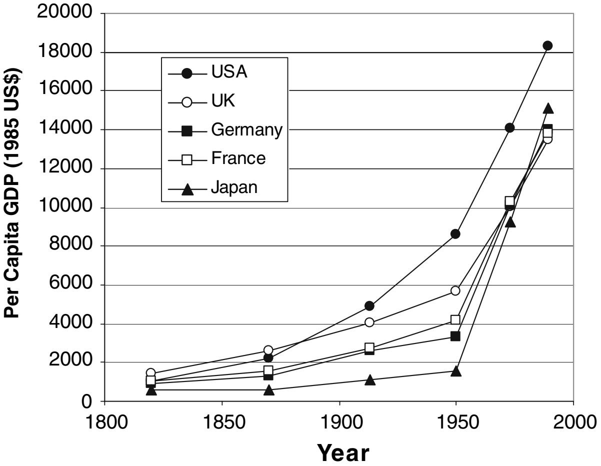


Fig. 2 Increase in per capita GDP from 1820 to 1989 in five industrialized nations (Maddison, 1991, Table 1.1)

increase 12–26 fold by 2100 (relative to 1990 values), and per capita affluence (GWP/person) 4–19 fold during this period.

The continuous progress in science and technology during the last two hundred years has played a key role in contributing to rising living standards (i.e., per capita GDP) in the industrialized nations. Three interrelated lines of evidence for this assertion will be discussed, (a) the general nature and drivers of technological innovation, (b) empirical confirmation for the so-called rebound effect that is often observed in response to efficiency improvements, and (c) factor analysis from neo-classical growth theory.

3.1 Technological innovation is directed by the profit motive

It should not be surprising that technological innovations have increased economic output and per capita affluence given that, most fundamentally, modern technologies are nothing more than highly efficient processes designed to convert large quantities of primarily non-renewable energy and mineral resources into a wide variety of products and services while at the same time minimizing the input of human labor. More specifically, advances in science and technology have increased affluence in three basic ways: first, by substituting capital and energy for labor, thereby significantly increasing labor productivity which translates into rising per capita production and consumption; second, by creating a very large number of new products and services that never before existed, thereby opening up new avenues of consumption and generating large demands; and third, by continuously increasing efficiencies, producing greater output with less input of labor, capital, energy, and mineral resources, thereby decreasing the costs of goods and services and thus stimulating their consumption (Braun, 1995; Schumpeter, 1934).

While many scientific insights and technological inventions occur randomly and by chance, the selection of successful technologies is anything but a random process. As Braun (1995, p. 21) notes:

> “In a Darwinian analogy, technological inventions may be regarded in the same light as spontaneous mutations of species. Inventions become successful innovations if society selects them.... only those technologies will be selected

> that can make money in the marketplace. In the case of process technologies, the selection mechanism is dominated by the ability of the technology to increase productivity, improve the competitive position, and increase profits for its owner.''

In a free market economy, businesses have two primary options for increasing their profits, specifically (a) by reducing the costs of production inputs such as capital, labor, and energy, and (b) by expanding sales of products or services either by decreasing their respective costs and thus becoming more competitive or by developing entirely new goods and creating new markets (Samuelson & Nordhaus, 1989). Since technological innovation plays such an important role in increasing profits in all these ways, it is not surprising that technological evolution is directed almost exclusively by the profit motive and only rarely by other societal or environmental concerns. If global collapse is to be avoided, future progress in science and technology must be guided by more than just the motive to increase profits for the owners of capital—a topic discussed in more detail in the policy Sect. (6) below.

3.2 The rebound effect

As mentioned above, technological efficiency improvements are an important means by which businesses reduce production costs and lower the price of goods and services, thereby stimulating consumer demand. The observation that efficiency gains do not necessarily decrease the use of limited resources but may rather stimulate their consumption as a result of efficiency-induced price reductions was first made by Jevons in 1865: ``It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to diminished consumption. The very contrary is the truth.'' (Jevons, 1865). The phenomenon of efficiency improvements stimulating the consumption of the very resources that were supposed to be conserved is termed ``rebound effect'' or Jevon's paradox.

Consider, for example, a hypothetical case in which the fuel efficiency for automobiles doubles from 15 to 30 miles per gallon, thereby decreasing the fuel costs per mile traveled by 50%, assuming constant gasoline prices. An engineering analysis would predict that the 100% increase in efficiency would result in exactly a 50% reduction in gasoline use. However, the lowered ``cost of service'' (i.e., cost per mile traveled) would enable people to use some of the saved fuel expenses to drive more, particularly if they had been restrained by a limited fuel budget from doing so before. As a result, total fuel use will ``rebound'' and some or all of the originally predicted fuel savings will be eliminated through additional consumption. In some cases, technological efficiency improvements may even backfire, resulting in consumption which exceeds the level prior to the initiation of efficiency measures.

According to Greening, Greene, and Difiglio (2000), there are four categories of market responses to efficiency improvements, specifically (a) direct rebound effects, which are responsible for the increased use of goods and services affected directly by their efficiency-induced price reduction, (b) secondary rebound effects, which lead to increased consumption of other goods and services as a result of real income increases, particularly if the direct rebound effect is relatively small (i.e., a re-spending effect), (c) economy-wide effects, primarily price and quantity readjustments, and

(d) transformational effects such as changes in consumer preferences, social institutions, and the organization of production.

There has been intense debate during the last 20 years regarding the effectiveness of energy efficiency improvements in reducing total energy consumption: some energy policy specialists claim that rebound and take-back effects are minimal while others maintain that most, if not all, efficiency gains are lost due to increased consumption (Bentzen, 2004; Brookes, 2000; Greening et al., 2000; Grubbs, 1990; Herring, 1999; Howarth, 1997; Inhaber & Saunders, 1994; Khazzoom, 1980; 1987; 1989; Laitner, 2000; Lovins, 1988; Saunders, 1992; 2000; Schipper & Grubb, 2000; Schurr, 1982). While neoclassical growth theory (see next section) predicts rebound and even backfire under certain conditions (Saunders, 1992; 2000), it has been extremely difficult to measure the overall effects of energy efficiency improvements on total energy use, a fact that should not be unexpected given the complex set of synergistic market responses listed above. It has been possible, however, to estimate the direct rebound effect in various cases (Bentzen, 2004; Binswanger, 2001; Hertwich, 2005), and there is now consensus that it is usually relatively small. For example, the rebound effect for fuel efficient cars (Greene, 1992; Greening et al., 2000) as well as for improved space heating technology (Haas & Biermayr, 2000) is about 10%-30%, indicating that efficiency improvements will be between 70–90% effective in reducing energy consumption in these specific cases.

There are several reasons that direct rebound effects are generally small. First, energy costs are often only a minor component of the overall cost of energy services so that reductions in energy costs due to efficiency improvements provide only a limited incentive to increase the level of service. Second, the demand for energy services is often cost-inelastic, especially in the household sector where energy services are near or at saturation (Khazzoom, 1980; Lovins, 1988). This is particularly the case in industrialized nations where markets for energy and consumer goods are saturated. However, the opposite is likely to be the case in developing nations where demand for many (basic) goods and services is still high. In this case, the direct rebound effect could be very large, particularly if the current inefficient technologies place a significant restraint on industrial production (Roy, 2000; Schipper & Grubb, 2000).

While the direct rebound effect is generally small, the secondary rebound effect is likely to be relatively large. In general, the smaller the direct rebound, the greater the secondary, because any savings not spent on the original service will be spent (sooner or later) on other goods and services. This re-spending effect is a major contributor to rising affluence and at the same time poses serious problems for resource conservation. Consider, for example, an individual switching to a more energy-efficient mode of transportation, e.g., from automobile to bicycle. The transportation money thus saved will be re-spent on other consumptive activities, most of which will require direct or indirect (embodied) energy. As Hannon (1975) has shown, unless a consumer is informed and seriously concerned about the energy content of different products and services, he is unlikely to select those with low energy intensity and therefore could very well inadvertently contribute to increased total energy consumption. The inherent problems associated with re-spending effects and their management will be discussed in the policy Sect. (6).

In conclusion, rebound effects, both direct and indirect, in response to efficiency improvements are a major cause for the rising per capita affluence in industrialized nations. Neoclassical growth theory provides additional macro-economic evidence that progress in science and technology has played a key role in promoting economic expansion, a topic discussed below.

3.3 Neoclassical growth theory

In traditional agricultural societies, economic output (primarily in the form of food products) depended on only two factors of production: land and labor. The use of "capital" such as simple tools and machinery played only a minor role. With the Industrial Revolution, however, the contribution of land declined (see above discussion) and that of capital and energy increased substantially. Consequently, neoclassical growth theory generally utilizes production functions in which economic output (Q) depends on capital (K), labor (L), and (sometimes) energy (E) (Ayres & van den Bergh, 2005; Ayres and Warr, 2005; Beaudreau, 2005; Samuelson & Nordhaus, 1989; Solow, 1957). More recently, the contribution of technological change has also been incorporated into production functions, as for example by Saunders (1992):

$$Q = t_n \cdot F(t_K K,\ t_L L,\ t_E E) \tag{2}$$

where $t_n = e^{\lambda_n t}$ is neutral technological progress, $t_K = e^{\lambda_K t}$ is capital-augmenting technological progress, $t_L = e^{\lambda_L t}$ is labor-augmenting technological progress, $t_E = e^{\lambda_E t}$ is energy-augmenting technological progress (i.e., energy efficiency improvements), and λ_i are rate constants for the respective technological changes.

As shown in Fig. 3a, where each hyperbolic curve represents the same constant output (Q) as a function of capital (K) and labor (L), technological progress continuously reduces both capital and labor requirements, thereby moving the production possibility frontier ever closer to the origin. The mix of K and L to produce a given output Q, i.e., the exact position on the constant production curve, depends on relative factor prices. Because throughout history the cost of labor was

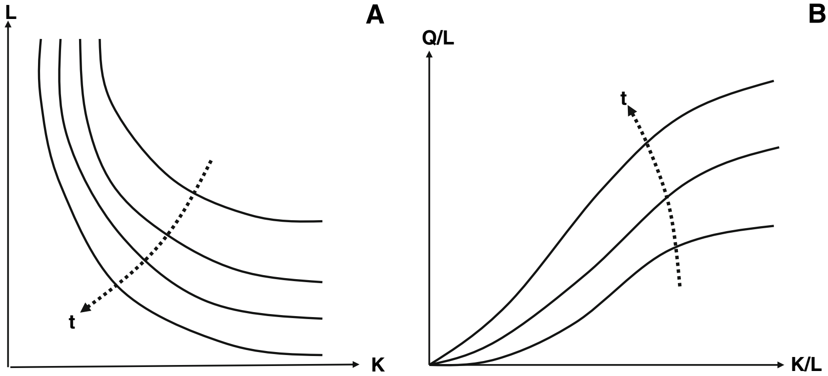


Fig. 3 (**A**) Time series of constant production curves as a function of capital (K) and labor (L). Technological progress continuously reduces both capital and labor requirements with time, thereby moving the production possibility frontier ever closer to the origin. Adapted from Salter (1960). (**B**) Labor productivity (Q/L, economic output per unit labor) grows not only as the ratio of capital to labor (K/L) increases, a process called capital deepening, but also with technological change, as indicated by the upward movement of the production functions with time. Adapted from Solow (1957)

generally higher than the cost of capital, technological progress has been more labor-saving than capital-saving, which is reflected by the faster approach of the constant production lines towards the K-axis than towards the L-axis.

The ongoing substitution of capital for labor results in a continuous increase in the ratio of K/L, a process called capital deepening. As shown in Fig. 3b, worker productivity increases not only with capital deepening but also with technological change, as indicated by the upward movement of the production functions with time, illustrated here for the simplified case of neutral technological progress (see t_n in Eq. 2). The critical question is how much is technological progress, compared to increases in capital and labor, responsible for the total growth in economic output?

To answer this question, economists use the following fundamental equation of growth accounting (Samuelson & Nordhaus, 1989):

$$\%\ Q\ \text{growth} = \%\ L\ \text{growth} + \%\ K\ \text{growth} + TC \tag{3}$$

where TC represents technological change, also called total factor productivity (TFP). The contribution of technological change cannot be measured directly but is determined indirectly as the residual after all other components of output (Q) and input (L, K) are quantified and accounted for. Technological change not only includes the effects of scientific advances and technological innovation but also improvements in the education of the labor force and economies of scale. Table 1 lists several estimates for the contribution of total factor productivity (TFP) to economic growth in the United States during different time periods. During times of rapid industrialization in the U.S. (i.e., from 1870–1960), technological change was responsible for ca. 80–90% of the observed economic growth. The contribution of technological change to economic expansion seems to have declined in more recent years, possibly indicating a slowing down of technological progress due to the law of diminishing returns which is commonly observed for R&D investments (Samuelson & Nordhaus, 1989; Tainter 1988). In conclusion, advances in science and technology have been the primary reason for the sharp rise in affluence which has been observed in industrialized nations during the last two centuries.

4 Technological progress significantly increases efficiency

As a result of advances in science and technology, both population size (P) and affluence (A) have increased substantially during the last two centuries, as indicated

Table 1 Contribution (%) of Total Factor Productivity (TFP) to economic growth in the United States during different time periods

Investigators	Time period	Growth due to TFP
Fabricant (1954)	1871–1951	90%
Abramovitz (1956)	1870s–1940s	90%
Solow (1957)	1909–1949	88%
Kendrick (1961)	1889–1957	80%
Denison (1985)	1929–1982	68%
Samuelson and Nordhaus (1989)	1948–1986	44%
Maddison (1991)	1913–1950	30%
Maddison (1991)	1950–1973	21%

by the 100-fold rise in global industrial output since 1750 (Gruebler 1994) and the 450-fold increase in GDP in the U.S. since 1820 (Maddison, 1991, Table A.2). This profound expansion of economic and industrial activity would have caused a much more serious strain on energy and material requirements and the environment if technological innovation (i.e., the T-factor in Eq. 1 above) had not also simultaneously improved the efficiencies of energy and materials use and reduced pollution. The key question, in the context of this paper, is whether efficiency improvements have been sufficient to reverse the rise of energy and materials use as well as environmental pollution, thereby promoting sustainability and preventing collapse?

In the most general terms, efficiency (e) can be defined as the ‘‘amount of benefit (B) derived per unit limited resource[3] (R)’’, or equivalently:

$$e = \frac{B}{R} \tag{4}$$

Increases in technological efficiency can be used to (a) increase benefits while holding resource use constant, (b) reduce resource use while holding benefits constant, or (c) increase benefits while simultaneously decreasing resource use. Historical data (see below) indicate that efficiency improvements generally have not been able to reverse the growth in material, energy, and land use or environmental pollution.

4.1 Energy efficiency and total energy use

The energy efficiency (e_e) of the total economy, which is the inverse of energy intensity (EI), is defined as:

$$e_e = \frac{GDP}{TPES} = \frac{1}{EI} \tag{5}$$

where GDP is the gross domestic product ($US) and TPES is the total primary energy supply (EJ).

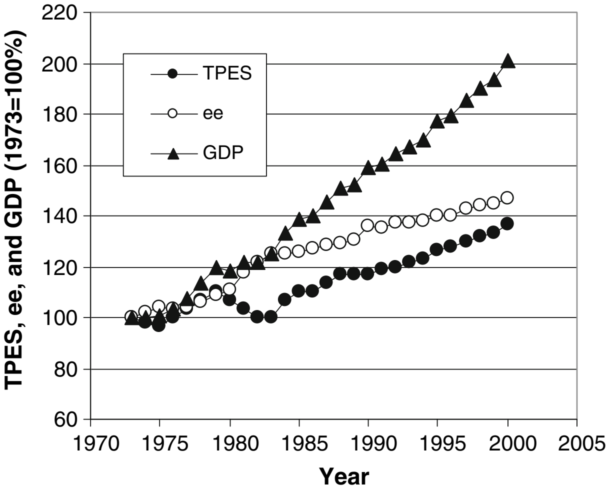
As shown in Fig. 4, increases in energy efficiency (e_e) by almost 50% in all IEA (International Energy Agency) nations from 1973 to 2000 were insufficient to halt or reverse the continuing rise in the required total primary energy supply which grew more than 36% during this period. The reason for the failure of energy efficiency to reverse the growth in energy consumption is that economic expansion (100%) far exceeded improvements in efficiency (50%). If the size of the economy of IEA countries had remained constant, total energy use would have decreased by more than 30%, resulting in a significant reduction in the use of scarce non-renewable energy resources.

Given that the size of the economy is the product of population size and per capita affluence (see Eq. 1), it it instructive to look at the contribution of population growth to the overall increase in total energy use. For example, the growth of the world population from 1850 to 1990 was responsible for 52% of the concomitant 20-fold increase in energy consumption, whereas in the United States during the same

---

[3] A limited resource may be a non-renewable or renewable fuel and mineral, the waste absorption capacity of the environment, or even time.

Fig. 4 Total primary energy supply (TPES, EJ), energy efficiency of the total economy (e_e), and gross domestic product (GDP, \$US) in IEA (International Energy Agency) countries from 1973 to 2000 (OECD/IEA, 2004)



period, population growth accounted for 66% of the 36-fold increase in energy use—and even 93% during 1970–1990 (Holdren, 1991). Considering that population growth has been a major cause for increased energy use in the past, it is clear that the stabilization and reduction of population size will be an important means of reducing energy consumption in the future (see also Sect. 6.1).

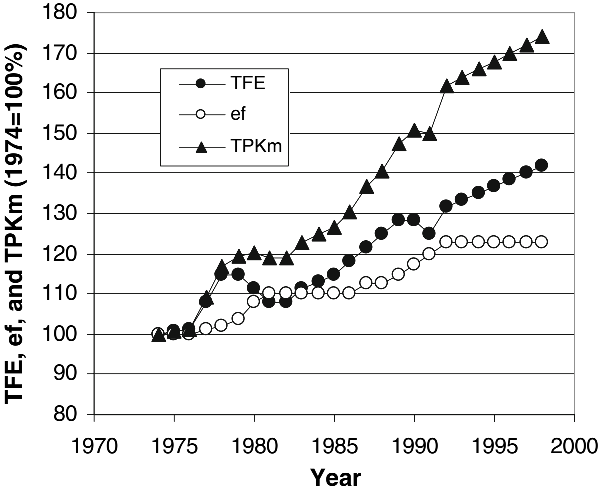
4.2 Automobile fuel efficiency and total automobile fuel use

The fuel efficiency (e_f) for a given automobile fleet is defined as:

$$e_f = \frac{TPKm}{TFE} \tag{6}$$

where TPKm is the distance driven (total passenger kilometers) and TFE is the total fuel energy (EJ) used for automobile transportation.

Fig. 5 Total fuel energy used for transportation by automobiles (TFE, EJ), fuel efficiency of the entire automobile fleet (e_f), and total passenger kilometers driven (TPKm, km) in IEA (International Energy Agency) countries from 1974 to 1998 (OECD/IEA, 2004)



The situation for automobile fuel use and efficiency is similar to that observed for total primary energy supply and energy efficiency. As shown in Fig. 5, automobile fuel efficiency improved by 20% from 1974 to 1998 in IEA countries but this was accompanied by a more than 40% rise in consumption of automobile fuel. The primary reason for the failure of automobile efficiency improvements to reverse the growth in fuel use is that the number of total passenger kilometers increased by almost 75% during this period. If it had remained constant, the use of automobile fuel energy would have declined by 20% which would have led to a significant conservation of fossil fuels.

4.3 Lighting efficiency and total energy use for public lighting

The lighting efficiency (e_l) for illuminating public roads in the United Kingdom is:

$$e_c = \frac{LS}{TEUL} \tag{7}$$

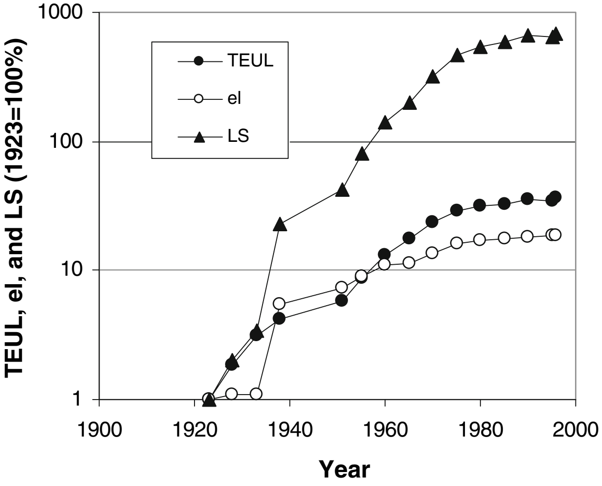
where LS is the amount of lighting service (lumen-hr) provided and TEUL is the total energy use for public lighting (GWhr).

As shown in Fig. 6, the efficiency of lighting (lamp efficiency, lumens/watt) increased almost 19-fold from 1923–1996. However, this large efficiency improvement did not reduce the amount of energy used in public lighting, which increased more than 36-fold during the same period because of the almost 700-fold expansion in public lighting service. Thus, lamp efficiency improvements did not decrease energy use but instead facilitated the expansion of public lighting, a classic example of the rebound effect.

4.4 Efficiency of materials use and total material requirements

The efficiency of materials use (e_m) for the total economy, which is the inverse of materials intensity (MI), is defined as:

Fig. 6 Total energy use for public lighting (TEUL, GWhr), lighting efficiency for illuminating public roads (e_l), and lighting service provided (LS, lumen-hr) in the United Kingdom from 1923 to 1996 (Herring, 1999). Please note logarithmic scale



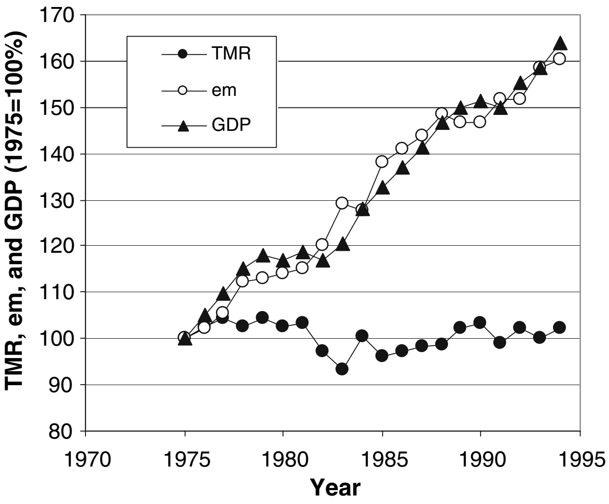


Fig. 7 Total material requirements (TMR, tons), efficiency of materials use for the total economy (e_m), and gross domestic product (GDP, $US) in the United States from 1975 to 1994 (Adriaanse et al., 1997)

$$e_m = \frac{GDP}{TMR} = \frac{1}{MI} \tag{8}$$

where GDP is the gross domestic product ($US) and TMR is the total material requirement (tons).

Figure 7 shows the total material requirements (TMR), the gross domestic product (GDP), and the efficiency of total material use (e_m) in the United States from 1975 to 1994. While e_m increased about 60% during this 18 year period, the total use of materials did not decline but remained constant as a result of a concomitant 60% increase in GDP. If there had been no economic growth, total material requirements would have been reduced by almost 40% during this period. Since the U.S. population grew by ca. 17% from 1975 to 1994 (Hobbs & Stoops, 2002), total material requirements could have been reduced by approximately the same percentage during this time interval if the United States had stabilized population numbers.

4.5 Corn yields and planted acreage

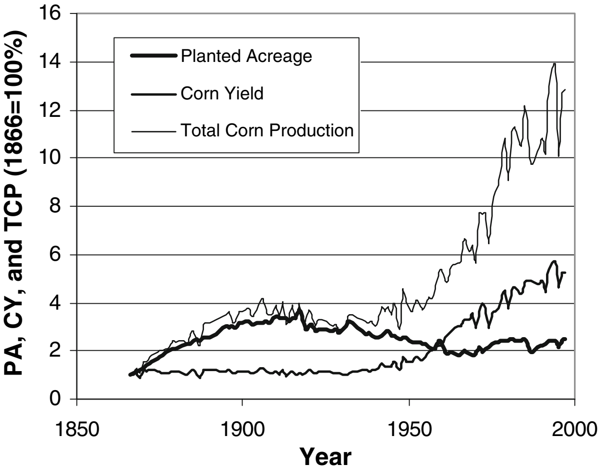
The efficiency of corn production (e_{corn}), i.e., the corn yield, is defined as:

$$e_{corn} = \frac{TCP}{PA} \tag{9}$$

where TCP is total corn production (tons) and PA is planted acreage (hectares).

As shown in Figure 8, corn production in the United States falls into three distinct phases. During the first phase (c. 1860 to 1920), corn yield was essentially constant and total corn harvests were directly proportional to the planted acreage, both of which increased approximately four-fold during this period. During the second phase (1920 to 1950), corn yields increased slowly (almost doubled) but total corn production remained constant, which resulted in a significant decrease of acreage dedicated to growing corn. This is one of the rare examples

Fig. 8 Planted acreage (hectares), efficiency of growing corn (e_{corn}), i.e., the corn yield (CY), and total corn production (TCP, tons) in the United States from 1866 to 1997 (USDA, 2005)



where efficiency improvements were translated into an actual reduction of limited resource use, in this case agricultural land previously allocated to the cultivation of corn. During the third phase (1950 to present) corn yields have increased continuously and have more than tripled. During this period, planted acreage has remained constant and total corn production has increased more than three-fold in direct proportion to corn yields. This is a typical case in which efficiency gains have been used to increase production and profits. If total corn harvests had remained constant since 1950, the extremely large increase in corn yields from 38 bushels/acre in 1950 to 127 bushels/acre in 1997 could have been used to conserve ca. 50,000 acres of farmland. It is unfortunate that gains in corn yield were not used to convert unused farmland back into prairies and forests which would have been beneficial both in terms of eco-system restoration and climate change mitigation (Huesemann, 2006) but instead were used to increase harvests to such an extent that the excess corn had to be fed to cattle so that farmers could remain profitable.

4.6 Carbon intensity and total atmospheric carbon dioxide emissions

Carbon dioxide (CO_2), an end-product of fossil-fuel combustion, is currently discharged without treatment into the atmosphere which serves as a sink for this very large and ubiquitous waste stream. Worldwide emissions of CO_2 are currently approximately 7 Gt per year (Marland, Boden, & Andres, 2002) and are expected to increase substantially unless strong counter-measures are taken (Huesemann, 2006). As a result of these anthropogenic carbon emissions, atmospheric CO_2 concentrations have risen 34% from pre-industrial levels of 280 ppm to approximately 375 ppm in 2003 (Keeling & Whorf, 2003) and are projected to increase to 550–970 ppm by 2100 (Huesemann, 2006; IPCC, 2001). Increasing atmospheric CO_2 concentrations are already producing global climate change, and many negative effects such as severe weather events, sea level rise, and the collapse of local eco-systems will increase both in frequency and scale unless a serious effort is made to decrease the carbon intensity of the global economy.

The efficiency of carbon use (e_c) by the total economy, which is the inverse of carbon intensity (CI), is defined as:

$$e_c = \frac{GDP}{Carbon} = \frac{1}{CI} \tag{10}$$

where GDP is the gross domestic product ($US) and "Carbon" is the total amount of carbon emitted (Gt). The carbon intensity of an entire economy (CI) is the product of the energy intensity of the economy (EI_{eco}) and the carbon intensity of the fuel supply (CI_{fuel}):

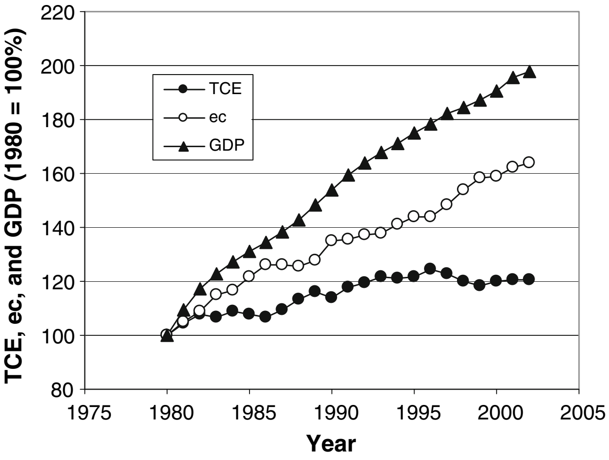
$$CI = \frac{Carbon}{GDP} = \frac{Energy}{GDP} \cdot \frac{Carbon}{Energy} = EI_{eco} \cdot CI_{fuel} \tag{11}$$

Historical data indicate that globally energy intensity (EI_{eco}) has decreased at a rate of ca. 1% per year in the last century (Jochem, 2000; Nakicenovic and Gruebler, 1993; Nakicenovic, Gruebler, & McDonald, 1998). Similarly, the carbon intensity of the global fuel supply (CI_{fuel}) has declined globally by approximately 0.3% per year since 1860 (Nakicenovic, 1996) as high-carbon energy sources, such as wood and coal, have been gradually replaced by those with lower carbon content, such as natural gas, and, more recently, nuclear and renewable energy which contain no carbon.

Despite the steady decline in global carbon intensity (CI) at a rate of 1.3% per year, global carbon emissions still continue to rise because world-wide economic expansion (i.e., GWP growth) continues to outpace improvements in the efficiency of carbon use (e_c). For example, as shown in Fig. 9 for the United States during 1980–2002, despite a more than 60% increase in the efficiency of carbon use, which is equivalent to a 40% decrease in carbon intensity, total carbon emissions have not decreased but, instead, have increased by 20% due to the large increase (200%) in GDP that occurred during the same period.

As mentioned in Sect. 4.1., a significant contributor to the expansion of GDP and energy use is often population growth. Since the U.S. population grew by ca. 21% from 1980 to 2002 (Hobbs & Stoops, 2002), total carbon emissions could have been reduced by approximately the same percentage during this time period if the United

Fig. 9 Total amount of carbon emitted (TCE, Gt), efficiency of carbon use (e_c) for the total economy, and gross domestic product (GDP, $US) in the United States from 1980 to 2002 (U.S. DOE, 2003; U.S. OMB, 2004)



States had had a stable population. Similarly, future population growth is expected to have a significant effect on the increase in total carbon emissions. For example, several studies have shown that the projected population growth between 1985 and 2100 accounts for more than 33% of the future growth in CO_2 emissions globally and nearly 50% in the developing nations (Bongaarts, 1992; The Population Council, 1992).

In summary, efficiency improvements have generally not been able to reverse the growth in energy consumption, material use, or environmental pollution[4], both of which are the consequence of rapid economic development. Given that the law of diminishing returns applies to most technological innovations, it is questionable whether gains in efficiency can ever be made fast enough to outpace the negative effects of the global economic expansion which is predicted to increase GWP (gross world product) and per capita affluence ca. 10 to 20 fold by 2100 (Huesemann, 2006; IPCC, 2001). The only way that efficiency improvements will result in a reversal in the growth of energy and material use and environmental pollution is by enforcement of policies which limit the total amount of benefit or service (e.g., per capita GDP). This is discussed in more detail in the policy Sect. (6).

5 Is substitution the solution?

It could conceivably be argued that major technological breakthroughs—rather than slow incremental efficiency improvements—will ultimately reduce the T-factor in Eq. 1 to zero (or very close to zero), thereby completely uncoupling human economic and industrial activity from the environment and in that way prevent collapse. The reason for this optimistic viewpoint is that in the past, key technological innovations have often resulted in the replacement of non-renewable resources by renewables and polluting technologies by less-polluting ones. For example, replacement of coal by cleaner-burning natural gas has significantly reduced air pollution, and future replacement of fossil fuels by renewable energy sources such as wind, photovoltaics, and biomass should eliminate CO_2 emissions, thereby significantly reducing the threat of global warming (Huesemann, 2006). Similarly, fiber optic cables constructed from extremely abundant silica (i.e., quartz sand) have replaced wires containing scarce copper in communication systems, which more recently have become completely "wireless", thereby reducing material requirements even further.

While replacement of non-renewables with renewables would certainly promote long-term sustainability, it must be recognized that even technologies which are based completely on renewable energy and renewable material resources would have significant negative environmental impacts if deployed on the extremely large scales required to supply all products and services for the fast growing world economies. As has been described in more detail elsewhere (Huesemann, 2003, 2006), it would already be a considerable challenge to supply the current U.S. energy demand solely from renewable energy sources without causing major environmental impacts. For example, if ethanol from corn were to replace 100% of

---

[4] There are some exceptions: In response to environmental regulations, the release of a few selected pollutants has been reduced significantly or in some cases eliminated completely (see Sect. 6.2 for examples).

the gasoline consumed in the U.S. each year, all of the available U.S. cropland (i.e., both active and inactive, totaling about 190 million hectares) would have to be devoted to ethanol production, leaving no land for food production (Kheshgi, Prince, & Marland, 2000). Similarly, according to a U.S. wind energy potential study by Elliott, Wendell, and Gower (1992), at least 80 million hectares would have to be covered with windmills (50 m hub height, 250–500 m apart) to generate about 100 quads (106 EJ) of electricity which is equivalent to 100% of the current annual U.S. energy demand (U.S. DOE, 2004). It is highly questionable whether the public would tolerate huge wind farms covering large land areas given documented resistance due to concerns about blade noise and aesthetics (Dohmen & Hornig, 2004).

Another example of major technological innovations which may initially appear to be environmentally friendly but are later found to have serious hidden negative environmental impacts is the personal computer, which to the user, appears to be a very clean technology but in fact has enormous life-cycle costs (Williams, Ayres, & Heller, 2002). According to a recent study by Williams (2004), the materials intensity of computer manufacturing is ten times higher than that of automobiles or refrigerators, which is particularly alarming given the short useful life (1–4.5 years) of personal computers and the fact that 130 million computers are produced worldwide every year. Because of the need for ultra-clean air, the energy requirements for manufacturing computer microchips are immense: A typical chip plant uses the equivalent of the energy used by a U.S. city of 60,000–80,000 inhabitants (Betts, 2004).

Finally, it should be recognized that humans (and other animals) have certain resource requirements, called critical natural capital (Dresner, 2002; Gutes, 1996), which can never be replaced through technological innovation. These are, at minimum, clean water, clean air, a functioning eco-system to provide food and waste assimilation services, and a relatively stable climate upon which both the economy and social structure depend (Ehrlich, 1989). No technological advance, however impressive, can create substitutes for these basic necessities, indicating that it will be inherently impossible to decouple the human economy from the environment.

In conclusion, while technological breakthroughs and resource substitutions will certainly reduce energy and material requirements as well as pollution, environmental impacts of human economic activities cannot be completely avoided, i.e., the T-factor in Eq. 1 will never become zero[5]. This finding has important implications for policies designed to reduce environmental impact and to avert collapse. Since there is only limited potential for reducing the T-factor in Eq. 1, it follows that there cannot be unlimited growth in population (P) and affluence (A) if the goal is the reduction of total impact (I). Thus, strategies for averting global collapse will not only require far-reaching technological innovation and significant efficiency improvements but also the stabilization of and ultimately reductions in both population size and per capita affluence.

---

[5] The fact that all industrial and economic activities have inherently unavoidable environmental impacts is also supported by the second law of thermodynamics which states that "order" in the techno-sphere can only be created at the expense of generating "disorder" in the biosphere. For a detailed discussion of this topic, see Cleveland and Ruth (1997), Connelly and Koshland (1997), Faber, Niemes, and Stephan (1995), Glasby (1988), Huesemann (2001, 2003), O'Connor (1994), and Ruth (1993, 1995).

6 Policy options for preventing environmental and societal collapse

According to the IPAT Eq. 1 presented above, the negative impacts of resource extraction and pollution are a function of population size (P), per-capita affluence (A), and technological efficiency (1/T). In an effort to reduce various negative impacts (I), most attention has been focused on technological innovation (i.e., the development of eco-efficient technologies), and to a lesser degree on slowing of global population increase. Given that technological efficiency improvements have been generally unable to decrease the magnitude of resource use and pollution (see Sect. 4), it is highly unlikely that technological innovation alone will be sufficient to prevent environmental and societal collapse. Indeed, as Meadows et al. (2004) have recently shown by simulating various scenarios using their World3 model, global collapse can only be avoided by *simultaneously* stabilizing population size and affluence while at the same time employing the most eco-efficient technologies. Thus, sustainability can only be achieved if policies are developed and enacted which (a) rapidly reverse population growth, (b) improve technological efficiencies in order to reduce matter-energy throughput rather than supporting more economic growth, and (c) promote the transition to a steady-state economy in which per capita affluence is stabilized.

6.1 Reverse population growth

Empirical evidence has shown that human fertility can intentionally be decreased if the following two conditions are satisfied simultaneously: First, smaller families must be seen as desirable and in the individual's best interests. Secondly, women must have access to birth control and family planning services in order to limit their offspring to the desired number (O'Neill, MacKellar, & Lutz, 2001; Weeks, 1992). Science and technology can play a crucial role in both increasing the motivation to have smaller families and in providing improved birth control methods.

Motivation for smaller families, rather than access to modern contraception, is the primary determinant of fertility, accounting for roughly 90% of differences in total fertility rates among nations (Pritchett, 1994). Motivation to produce smaller families can be promoted by:

(a) Increasing education for women, thereby delaying the age of marriage as well as providing increased opportunities for entering the labor force and becoming financially independent. Education also introduces women to alternatives to a life with many children (Weeks, 1992). Recent studies have shown that improvements in female education alone could account for 40–67% of fertility decline in South American countries (Weeks, 1992) and that just one year of additional female schooling reduces fertility by 5–10% (Birdsall, 1994).

(b) Making reduced fertility economically advantageous by providing financial incentives for small families and disincentives for large ones. Incentives may include payments to couples for delaying pregnancies and for undergoing surgical contraception, giving women the opportunity to enter the paid labor force, and providing for housing and education of first and second children but not for additional children. Disincentives may consist of enactment and enforcement of child labor laws to prevent exploitation of children for economic gain by parents and others, taxation for any children that are born after the second one, and higher user fees for maternal care, educational services, and other public resources for additional children (Weeks, 1992).

(c) Providing social security and universal health care in order to reduce dependence on adult children.

(d) Changing cultural norms with regard to ideal family size.

The goal is to substantially reduce family size without employing methods which may be considered human rights violations. The modern western commitment to individualism, often socially irresponsible individualism, may lead western observers to identify certain harmless techniques and incentive structures as violation of the rights of individuals. An international consensus must be developed in which the individual is considered *not* to have the right to endanger the future of his society, his nation, other nations, or the earth through his unwise choice with regard to reproduction. The human rights of future generations to a life free from wars, famine, and disease caused by the excessive reproduction of their forbears should be guaranteed. Irresponsible reproduction should not be considered a ‘‘right’’ any more than any other act which endangers the well-being of society. Effective forms of incentive or social pressure, whether appealing or not to the western bias towards individualism, should not be gratuitously faulted.

Modern communication technologies, particularly television and the internet, are extremely powerful tools for changing cultural values and therefore could be employed to promote smaller families. As mentioned above, television has been successfully employed by corporations to quickly and effectively transform diverse traditional societies into globally standardized consumer cultures which embody highly materialistic values, often in direct opposition to the social values that were cherished previously. Clearly, television and radio should have great potential to change concepts of the ideal family size. Indeed, specially designed family planning television and radio soap operas that were broadcast to hundreds of millions of viewers in Brazil, India, Kenya, Mexico and other nations were shown to significantly reduce fertility rates, often within the short time periods in which the programs were aired. For example, the desired family size fell from 3.4 to 2.5 children between 1989 and 1998 in Brazil, and decreased from 6.3 to 4.8 children per woman in Kenya in direct response to family planning soap operas (Ryerson, 1995). Not only have these broadcast programs been highly effective in motivating couples to produce smaller families, they are also significantly less expensive than direct financial incentives which would be cost-prohibitive in such populous nations as India.

In addition to providing the means by which smaller family size becomes a desirable goal, science and technology can also play a crucial role in providing improved and more cost-effective birth control methods. The availability of oral contraceptives during the last forty years has already had a profound impact on fertility rates in all industrialized and some developing nations. Worldwide, there is still a desperate need for family planning, since there are currently at least 100 million women in the Third World who do not want additional children (Bongaarts, O’Neill, & Gaffin, 1997). Because of insufficient access to contraceptives, approximately one in every five births is undesired and 25 million abortions are carried out annually (Bongaarts et al., 1997). Clearly, this situation could improve greatly through the development and dissemination of less costly and more user-friendly birth control methods.

Despite the fact that in the past, scientific and technological revolutions resulted in increased human populations, there is no reason why modern science and technology cannot be used to produce the reverse effect. However, in order to achieve significant reductions in human fertility, progress in science and application of technology must be consciously directed towards this goal and not left solely to free market forces or the profit motive. For example, governments must have clear population policies and provide funding for advanced birth control methods. More importantly, governments should use the powerful media of television and radio to change cultural norms towards smaller family size. The challenge of reducing human population size will therefore not be primarily scientific or technological but rather the overcoming of strong resistance by many politicians as well as certain religious and business groups who believe that continued population growth is in their best financial or ideological interests despite the fact that it will hasten global environmental and societal collapse.

6.2 Improve efficiencies to reduce matter-energy use

In Eq. 4 above, technological efficiency (e) was defined as the "amount of benefit (B) derived per unit limited resource (R)", i.e., e = B/R. Accordingly, depending on whether the numerator or denominator is held constant, efficiency improvements can serve diametrically opposing goals: either various benefits (B) such as per capita GDP (affluence) can be increased while keeping resource use (R) constant or resource use can be reduced while keeping the amount of derived benefits constant. The analysis of historical data in Sect. 4 indicates that in free-market economies technological efficiency improvements were almost always used to promote growth in benefits and not reduction in resource use. Given that attaining sustainability almost certainly requires the stabilization of matter-energy throughput at lower than present levels, it is clear that "business as usual" efficiency improvements, because of their inability to reverse the growth in resource use, will not automatically translate into greater sustainability.

In order for technological efficiency to promote sustainability instead of hastening collapse, it will be necessary to first change our current goal of unlimited economic growth (B) to a reduction in overall matter-energy use (R), and then vigorously apply technological innovation to meet this new objective. Limiting and reducing the matter-energy throughput does not necessarily mean that economic growth must cease entirely, at least initially (see Sect. 6.3). Rewriting Eq. 4 as

$$B = eR \tag{14}$$

shows that the overall level of benefits (B) could remain constant or even grow moderately if the rate of efficiency improvements is equal to or greater than the rate of reduction in matter-energy use (R). For example, if the policy objective were merely to keep resource use and pollution at current levels (R = const), the total amount of benefits derived from goods and services could be allowed to grow at the rate at which efficiency improves. However, if the policy objective were to slowly decrease overall matter-energy throughput and pollution at, for example, 1% per year for the next 100 years (i.e., a three-fold reduction in R), gains in efficiency would need to be at least 1% per year during the same time period in order to ensure that the overall level of benefits would not decrease.

There are a number of policies which could be implemented to intentionally limit and reduce the total amount of matter-energy use and pollution. The most common ones are regulation and taxation, but it is likely that more innovative approaches will emerge in the future. Regulations have been effectively used in the past to reduce the amount of waste released into the environment and to conserve energy. For example, the outright prohibition of lead in gasoline, PCBs, and ozone-depleting chemicals almost completely halted the release of these pollutants into the environment (Meadows et al., 2004). Various air and water quality standards assure that waste discharges are strictly limited. Capping and trading schemes are also used to control the total amount of pollutants released into the environment while providing some flexibility (via pollution trading) in meeting overall discharge limits.

Similar types of capping schemes could also be applied to limit the total use of renewable and non-renewable minerals and fuels. Policies could be enacted, as has been already done for selected forests and fisheries, to limit the harvest of any renewable resource to its sustainable yield, thereby preventing the degradation of the ecosystems which provide these valuable goods (Diamond, 2005). Similarly, a maximum extraction rate (i.e., depletion quotas) for non-renewable minerals and fossil fuels could be agreed upon to assure the availability of these limited resources for future generations (Daly, 1980). Placing a maximum limit on the use of renewable and non-renewable resources would signal scarcity and result in commodity price increases, which, in turn, would stimulate technological innovation including efficiency improvements.

In terms of energy conservation, federal efficiency standards for household appliances and automobiles have been to a large degree successful in reducing energy use, but could have been more effective if rebound had been controlled by simultaneously increasing the price of energy via taxation or other measures (see below). Another approach to conserve fuel has been the reduction of speed limits to 55 miles per hour, but this strategy has been estimated to decrease gasoline consumption by only about 1.4% (Blair, Kaserman, & Tepel, 1984). Given that the same reduction in gasoline use could have been achieved by only a 3.4% increase in price, it appears that taxation of energy and resource use would be a very effective strategy (Blair et al., 1984).

Increasing the price of mineral and energy resources via taxation is probably the easiest way to reduce their overall use and simultaneously encourage technological innovation while avoiding rebound. Increased price generally translates into reduced resource use, as indicated by the inverse relationship between prices and electricity consumption per unit GDP in 49 countries (Birol & Keppler, 2000) and by the historical response to the oil crisis of the 1970s, which not only caused substantial increases in fuel prices and concomitant reduction in energy use but also stimulated efficiency improvements and research in renewable energy. Before implementing various taxation schemes, however, it would be best to first remove "perverse" subsidies and to internalize environmental and, in the case of energy, national security costs that are incurred by the U.S. to ensure continuous access to world oil supplies. Consider, for example, that if all hidden subsidies and externalized environmental and national security costs of road transport were to be accounted for, the true cost of gasoline in the U.S. would be $2 to $7 (by some estimates even $6 to $16) per gallon higher than is currently paid by consumers (ICTA, 1998; Myers & Kent, 2001). Both perverse subsidies and various cost externalization schemes keep the cost of resources artificially low, thereby encouraging wasteful use by consumers and providing no incentives for conservation via efficiency measures (Jochem, 2000). As a result of these market imperfections, over 300 billion dollars worth of energy is wasted in the U.S. each year (Myers & Kent, 2001).

If removal of perverse subsidies and internalization of externalized costs are unable to reduce overall resource use, it will be necessary to implement some type of ecological tax to further increase the price of minerals and energy. Because of the strong public resistance to tax increases, innovative approaches are needed to implement ecological taxes. A revolutionary proposal for ecological tax reform was made by Ernst Ulrich von Weizacker in Germany who recommended that income taxes be reduced to compensate for new energy taxes, thereby ensuring a fiscally neutral approach that keeps total taxes paid by the average consumer more or less the same. The ultimate goal of von Weizacker's ecological tax reform is the reduction of resource use and pollution in order to achieve sustainability while at the same time promoting both full employment via reduction of payroll taxes as well as increasing international competitiveness through technological innovation (Dresner, 2002). Unfortunately, despite the urgent need to carry out ecological tax reforms and abolish perverse subsidies, implementation of these sustainability strategies has been and most certainly will be vigorously opposed by powerful special interests such as resource-intensive industries which interpret such policies as threats to profit margins and even survival. At this point we need to ask what is ultimately more important: the survival of corporations unwilling to change or the survival of civilization as we know it?

How much more can the efficiency of resource and energy use be increased? Estimates range from 4-fold (Von Weizacker, Lovins, & Lovins, 1998) to 10-fold (Cleveland & Ruth, 1999), and even 50-fold for specific energy end-use efficiency improvements (Nakicenovic & Gruebler, 1993). Some of the higher estimates might very well reflect unrealistic technological optimism since there are inherent thermodynamic limits to efficiency improvements (Balzhiser, Samuels, & Elisassen 1972) and since, in the words of Hermann Daly, one cannot indefinitely "angelize" the economy (Dresner, 2002). For example, there is a fundamental minimum amount of energy required to do a certain amount of work and it will always take 4.2 joules to heat a gram of water by 1°C. Similarly, there are minimum material requirements for consumer products and services.

Finally, we need to address a question that is rarely asked, that is whether life in an ultra-efficient technocratic society would really be preferable. It probably would not, for the following reasons: First, given that in such a society, efficiency (e) would be very close to its maximum value and therefore essentially constant, any unexpected change in the supply of energy and mineral resources (R) would, according to Eq. 14 above, immediately result in a concomitant decrease in benefits (B). In the past, for example after the oil crisis of the 1970s, our response to a sudden decline in crude oil availability was to increase technological efficiencies to keep benefits from falling, i.e., the detrimental effects of sudden fuel limitations were buffered by both short- and long-term increases in energy efficiency. This type of response would not be possible in an industrial society where all processes already operate at close to maximum efficiency. Consequently, such a society is likely to become much more vulnerable to resource shortages since these would translate directly and immediately into painful reductions in living standards.

Second, because of the increasing need for continued technological innovation in order to maintain all processes operating at optimum efficiency, dependence on technical experts would increase. While this would likely be welcomed by most scientists and engineers, the public could interpret the increasing power of technocracy as a threat to democracy. Third and finally, too much focus on efficiency as a way to achieve a sustainable future could conflict with other societal values such as freedom, creativity and aesthetics (McDonough & Braungart, 2002).

In conclusion, significant improvements in technological efficiency are possible before thermodynamic limits are reached. However, gains in efficiency will only result in greater sustainability if they are used to reduce the total matter-energy throughput rather than promote economic growth. In order to achieve a reduction in both resource use and pollution, it is necessary to remove perverse subsidies which encourage wasteful behavior, enact regulations that limit waste discharges and the depletion of non-renewable minerals and fuels, and implement ecological tax reforms that increase the price of resources, thereby promoting both conservation and technological innovation while avoiding rebound. It is clear that there are both technical and policy means to achieve sustainability. However, any changes in policy are likely to be vigorously opposed by special interests and large increases in efficiency might ultimately be considered undesirable by the public because of increased vulnerabilities to resource shortages, greater dependence on technocrats, and threats to existing social and aesthetic values.

6.3 Stabilize affluence at sustainable levels

Given that (a) matter-energy throughput must be reduced and stabilized at sustainable levels, and (b) technological efficiency improvements have both practical and theoretical thermodynamic limits, it follows that current trends of increasing per capita affluence cannot be continued *ad infinitum*. Consequently, our current growth-oriented economy will sooner or later have to become a steady-state economy, where per capita GDP is kept constant. In this new sustainable society, qualitative development would take precedence over quantitative growth in the consumption of goods and services[6].

This concept is not new—in fact, more than 150 years ago, John Stuart Mill wrote that a ''stationary state'' was consistent with the limits of the earth and could support an evolving and improving society:

> ''I cannot.... regard the stationary state of capital and wealth with the unaffected aversion so generally manifested towards it by political economists of the old school. I am inclined to believe that it would be, on the whole, a very considerable improvement on our present condition. I confess I am not charmed with the ideal of life held out by those who think that the normal state of human beings is that of struggling to get on; that the trampling, crushing, elbowing, and treading on each other's heels.... are the most desirable lot of humankind..... It is scarcely necessary to remark that a stationary condition of

---

[6] It has been argued that GDP can in principle increase ''indefinitely'' because it only reflects the amount of money circulating through the economy. This is correct but in order for GDP growth to continue without concomitant material consumption, people would have to focus on buying and selling personal services that do not require material and energy resources. This type of GDP growth would not result in a rise in material affluence as has been experienced in the last two centuries (Dresner, 2002, p. 105).

> capital and population implies no stationary state of human improvement. There would be as much scope as ever for all kinds of mental culture and moral and social progress; as much room for improving the art of living, and much more likelihood of its being improved.'' (Dresner, 2002, p. 257).

John Stuart Mill's ideas were not implemented because the economic system at the time was, as it is today, based on the ethic of utilitarianism which can be summarized in Jeremy Bentham's moral principle ''maximum happiness for the greatest number of people''. Unfortunately, there are two fundamental flaws in this form of utilitarianism. First, issues of justice and equity are avoided since it is of no concern whether the happiness of the majority is gained at the expense of other classes, nations, or species, the environment or future generations. It is for this reason that crude exploitation and its many unfortunate consequences are rampant in economic systems based on utilitarian philosophy. Second, in utilitarianism, happiness is equated implicitly with materialism, which involves the assumption that maximum consumption of goods and services will increase economic and personal well-being (Desner, 2002).

The utilitarian assumption that ''money buys happiness'' is based on evidence that at any given point in time, subjective well-being increases with income in a curvilinear fashion similar to that found in the substrate saturation kinetics of biological systems[7]: the curve increases steeply in the low-income region but levels off above income levels required to satisfy basic needs (Frank, 1999; Frey & Stutzer, 2002). The reason that wealth correlates with happiness, albeit weakly (r^2 = 0.15–0.20, Argyle, 1987), should be obvious: higher income provides more personal choices, enables conspicuous consumption to raise one's relative social status, and eliminates concerns about how to meet basic needs.

However, there is a paradox: while higher relative income of individuals is associated with greater subjective well-being at any given point in time, an increase in average affluence of entire nations (i.e., per capita GDP) over extended time periods has yielded no significant gains in happiness. For example, although personal income in the U.S. quadrupled from 1930 to 1990, the proportion of people considering themselves ''very happy'' remained more or less constant (around 33%) during the same time period (Myers & Diener, 1996). Despite the fact that per capita income in Japan rose six-fold from 1958 to 1991, the average life satisfaction rating remained constant (Frey & Stutzer, 2002). Similar results have been reported for other industrialized nations (Diener & Oishi, 2000). Clearly, the key utilitarian assumption upon which our economic system is based, namely that more economic growth and ever rising affluence will increase well-being and happiness, is false and in serious need of revision.

There are at least three reasons for this paradox:

1. As Aristotle pointed out more than two thousand years ago, human desires are by their very nature insatiable (Lane, 2001). Shortly after a material desire has been fulfilled, a sense of dissatisfaction soon develops resulting in further craving. This mechanism can be described in standard economic terms (Samuelson & Nordhaus, 1989): as long as an object is unavailable and scarce, it has high value and we strive for it, expecting to gain happiness from

---

[7] It is interesting to note that even at the molecular level, the active sites of enzymes also become with increasing substrate concentration saturated in a curvilinear fashion (Nelson & Cox, 2005).

its possession. But as soon as we have obtained the desired object, it is no longer scarce, and thereby becomes less valuable and less able to generate happiness. We then repeat this cycle by selecting another scarce item for which we strive, unfortunately without ever finding lasting fulfillment or contentment.

2. As was pointed out earlier, it is to a large degree relative rather than absolute income that determines one's social position as well as feelings of achievement and superiority. This accounts for the fact that a large fraction of income, at least 50% or more (Jackson & Marks, 1999), is spent on competitive, or in Thorstein Veblen's words, conspicuous consumption (Frey & Stutzer, 2002; Schor, 1992). The problem is that consumption of positional goods looses its ability to raise social status as soon as many others are able to purchase the same status symbols. As long as the relative income distribution remains more or less constant, increasing average affluence (per capita GDP) will not enhance an individual's social position or the sense of well-being derived from it. The end result is that people, like addicts, are caught on a hedonic, positional treadmill (Lane, 2001; Schor, 1992), consuming ever more status symbols, thereby raising total consumption of goods and services (per capita GDP) without obtaining greater happiness.
3. Finally, the frantic pursuit of materialism deprives people of opportunities to receive more meaningful satisfaction from the numerous social, cultural, and spiritual activities that are well known to promote happiness and feelings of well-being. As a result, individuals possessing strong materialistic values generally experience low life-satisfaction and often exhibit symptoms of low self-esteem, depression, anxiety, somatic ailments, personality disorders, antisocial or addictive behavior (Kasser, 2002).

The fact that material consumption above levels required to meet basic needs fails to increase subjective well-being not only deprives neoclassical economists of their key justification for promoting continuous economic growth but at the same time provides favorable data for those concerned with achieving societal sustainability and preventing collapse (Jackson, 2005). It appears that a reduction and stabilization in average affluence (per capita GDP) will not seriously affect human happiness as long as basic needs can be met, the relative income distribution remains about the same, and people learn to exhibit their social status in non-consumptive ways. In fact, given that a reduction in production and consumption would release more time and energy for the pursuit of other social, cultural, and spiritual activities known to substantially increase subjective well-being, it is possible that life in a steady-state economy where material consumption is reduced to more sustainable levels might be considerably more enjoyable.

The transition to a sustainable society with a smaller per capita ecological footprint would be greatly accelerated if there were policies to maximize happiness and well-being instead of material affluence and per capita GDP. These new policies could promote factors already known to significantly improve subjective well-being in non-materialistic ways such as more time for family and friends, stronger communities, satisfying work, leisure to develop talents (Durning, 1992; Frank, 1999; Hamilton, 2003), low unemployment (Oswald, 1997), absence of poverty (Kasser, 2002), decentralized local control of government and direct democratic participation

(Frey & Stutzer, 2002)[8]. Unfortunately, all of these non-consumptive, low-impact sources of happiness are presently treated as market externalities (Lane, 2001) which accounts for the failure of our growth-oriented economic systems to improve subjective well-being. Indeed, when many of the social and environmental costs of GDP growth are accounted for, as has been done using the Index of Sustainable Economic Welfare developed by Daly and Cobb (1989), it is found that sustainable economic welfare in many western industrialized nations grew more or less in direct proportion to GDP until about the mid-1970s or early 1980s but has since stabilized or declined despite continued economic growth (Castaneda, 1997; Diefenbacher, 1994; Jackson and Stymne, 1996; Stockhammer, Hochreiter, Obermayr, & Steiner, 1997). Much more research by social scientists and economists is needed to study the non-materialistic sources of subjective well-being and to design ‘‘happiness functions’’ that could be used to inform economic policy (Hamilton, 2003).

Effective methods of reducing material consumption to sustainable levels include the dissemination of information on ways in which needs and desires may be satisfied, including the aspiration for higher social status, in non-materialistic ways. It is well known that status symbols are socially constructed (Jackson, 2005). Consequently, conspicuous consumption as currently presented in television commercials and movies is not the only way in which social position may be displayed. The powerful medium of television could be used to promote non-materialistic status symbols. An individual might be considered to be of higher social status based on a happy and a harmonious family life, extensive community service as well as charitable contributions and activities.[9] Movies on television and elsewhere could promote non-materalistic, low-impact life-styles (Myers, 2003). Standard commercials and the consumption of luxury goods could be heavily taxed (Frank, 1999; Frey & Stutzer, 2002; Hamilton, 2003). If television could transform the entire planet into a global materialistic consumer culture within just 50 years, it could also be used to efficiently promote alternative non-materialistic lifestyles and sustainable consumption. Of course, this would require major changes in the control of mass media and, as discussed below, is likely to be met with strong resistance by many powerful special interests.

In conclusion, a steady-state economy in which material consumption (‘‘affluence’’) is reduced to a sustainable level while maintaining or even increasing subjective well-being will only be possible if people learn to satisfy non-material needs and desires in non-materialistic ways. As stated by Meadows et al. (2004, p. 262):

> ‘‘People don’t need enormous cars; they need admiration and respect. They don’t need a constant stream of new clothes; they need to feel that others consider them to be attractive, and they need excitement and variety and beauty. People don’t need electronic entertainment; they need something interesting to occupy their minds and emotions. And so forth. Trying to fill real

---

[8] In an interesting study of the influence of direct democracy on subjective well-being in different Swiss cantons (states), Frey and Stutzer (2000) found that direct democratic participation via popular referenda had a greater effect on happiness than living in the top rather than in the bottom of the income category.

[9] Some creativity will be needed to express social status in non-consumptive ways. Here we can learn from the military which for many years has successfully employed very simple and inexpensive symbols such as stars and stripes on uniforms to exhibit rank.

> but nonmaterial needs—for identity, community, self-esteem, challenge, love, joy—with material things is to set up an unquenchable appetite for false solutions to never satisfied longings. A society that allows itself to admit and articulate its nonmaterial human needs, and to find nonmaterial ways to satisfy them, would require much lower material and energy throughputs and would provide much higher levels of human fulfillment.''

There are a number of important questions which must be addressed through future research on sustainable consumption: How much can material consumption and the per-capita footprint in industrialized nations be reduced from current levels? What are the minimum material and energy requirements for meeting basic needs? Can consumptive activities be ranked based on their ''well-being/material input'' ratio, with the goal of optimizing happiness and minimizing material and energy use.

It appears that there are two basic strategies for reducing total material consumption. First, by eliminating any type of consumption that is presently used to satisfy non-material needs, it may be possible to reduce per-capita consumer expenditures by more than 50% (Jackson & Marks, 1999). Second, the remaining material needs for food, housing, health, and transportation could be met with less environmental impact if there were specific policies to promote ''green'' consumption alternatives. For example, by switching from the current meat-based diet to a more vegetarian one, land and energy use as well as greenhouse gas emissions associated with food production could be reduced considerably while at the same time improving health (Barnard, Nicholson, & Howard, 1995; Bender, 1994; Carlsson-Kanyama, 1998; Duchin, 2005; Gerbens-Leenes & Nonhebel, 2002; Goodland, 1997; Kramer, Moll, Nonhebel, & Wilting, 1999). Also, the life-span of household goods could be increased by making them more durable, thereby reducing their rate of consumption (Cooper, 2005). In addition, fuel requirements for transportation could be decreased substantially if cities were modified so that work and leisure locations could be safely reached by foot, bicycle, or public transportation, thereby making use of the personal automobile superfluous.

A switch to green consumption will only have a marginal positive environmental effect if per-capita income remains constant or continues to rise. This is because any money saved as a result of consuming the often more cost-effective greener goods and services is likely to be re-spent on other products, resulting in more resource consumption and pollution (Chalkley, Billett, & Harrison, 2001). For example, Alfredsson (2004) recently presented hypothetical green consumption scenarios for food, travel, and housing in Sweden and found that about 50% of the saved money is likely to be re-spent on other green products and services, thereby taking back approximately 33% and 20% of the initial energy and greenhouse gas reductions, respectively. Moreover, by around 2020, the resulting small decrease in household energy use (13%) and CO_2 emissions (25%) would be outpaced by even the most modest growth in income (i.e., only 1% per year), thereby nullifying any potential benefits of green consumption alternatives. Similarly, Hannon (1975) showed more than 30 years ago that per capita energy consumption is linearly related to personal income. As a result of the re-spending effect, it is extremely difficult to reduce per-capita energy consumption unless total income is reduced. Finally, even if per-capita income were to be significantly reduced by imposing

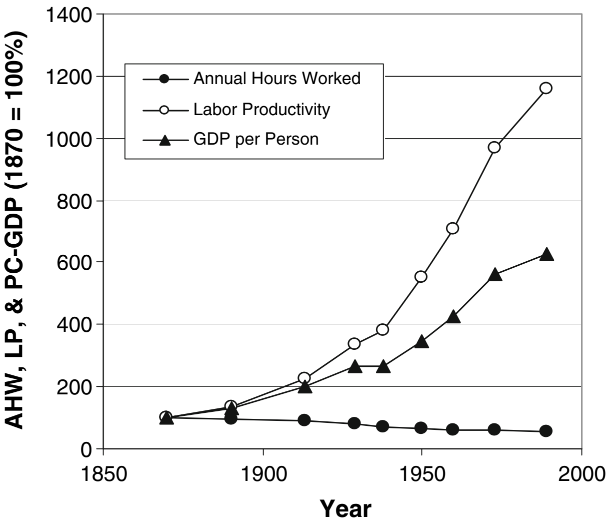


Fig. 10 Annual hours worked (AHW, hr) per employed person, labor productivity (LP), and per capita GDP (PC-GDP, $US) in the United States from 1870 to 1989 (Maddison, 1991, Appendix C)

environmental taxes, the problem of allocating tax revenues arises. Unless these are reinvested in natural capital and used for the restoration of the environment (Rees & Wackernagel, 1995), government revenues generally will be circulated back into the economy in the form of salaries and goods, thereby stimulating material consumption (Sanne, 2000). In conclusion, any financial savings obtained through the elimination of conspicuous consumption through green consumption alternatives will likely be re-spent[10] on the consumption of other goods and services unless total per-capita income is reduced.

A reduction in per-capita income is a key requirement for achieving environmental and societal sustainability in industrialized nations. Given that social science research into loss aversion has shown that most people are unwilling to give up income they already have (Kahnemann & Tversky, 1984), the crucial policy question becomes how to convince people to give up income and reduce material consumption. Before attempting to address this question, it must be recognized that gains in labor productivity due to technological innovation can be used to either increase per-capita income or decrease working time, or both (Ausubel & Gruebler, 1995; Schor, 1992). As shown in Fig. 10 for the U.S. from 1870 to 1989, the almost 12-fold increase in labor productivity (GDP output per person-hour worked) was converted into a 6-fold increase in affluence (per capita GDP) and a ca. 50% reduction in total hours worked (i.e., from 2964 to 1604 hours per year). In a perfectly free market, workers could choose to split the benefits derived from labor productivity gains into their preferred mix of income and leisure time. Unfortunately, as Schor (2005) has shown, there is currently a structural bias towards increased working hours which is due to various employer incentives.

Given that U.S. labor productivity has more than doubled since 1948, we could produce today a 1948 standard of living, which was generally acceptable to our

---

[10] Even if the accrued savings are not immediately spent but rather placed in a bank account or otherwise invested, they will eventually be spent in the future. Thus, saving results in delayed consumption.

parents and grandparents, by working only 4 hours a day (Schor, 2005). Instead, because of structural biases in the labor market and the endless promotion of conspicuous consumption by the mass media, Americans now work 200 h more per year than 30 years ago (Schor, 1992, 2005, Table 2). By contrast, people in other industrialized nations work less and have more leisure time. For example, in the year 2000, German employees worked approximately eight weeks (i.e., 347 h) less per year than their American counterparts (Schor, 2005), and the French have adopted a 35-hour week by law (Hamilton, 2003). Thus, it is in principle possible to redirect labor productivity gains into increases in leisure time rather than income, thereby giving people the opportunity to engage in activities known to improve personal well-being much more than does conspicuous material consumption.

There is likely to be strong resistance to the transition to a sustainable society in which material consumption and work time is reduced, specifically by those who benefit most from the current economic order. We refer to those who comprise approximately 1% of the total U.S. population but who own a disproportionately large fraction of income-producing property, i.e., about 68% of business equity and 50% of all stocks and bonds (Kivel, 2004). The singular objective has been to maximize returns on investments (i.e., profits), allowing this minority to maximize luxury and leisure as well as to eliminate their need to work. Since profits are generally the result of minimizing costs of labor and production inputs and maximizing income from product sales, it is clear that profits are maximized when employees' working hours and production output are maximized and wages are minimized. Thus, the very idea of reducing working time as well as material production/consumption will be completely unacceptable to the enormously influential because this will significantly reduce their own access to luxury and leisure.

In addition, the concept of a steady-state economy which is characterized by zero economic (GDP) growth is unlikely to be welcomed by any segment of society because if there is no further economic growth, there no longer will be any hope for the working classes to achieve a better standard of living even at some imaginary time in the future. In the absence of the pacifying effect caused by materialism coupled with the expectation of ever rising affluence, public discontent could increase and be accompanied by a demand for a more equitable distribution of wealth. This indicates that ultimately a sustainable world is possible only if there is an equitable distribution of wealth, not only within nations but between nations as well.[11] However, as history has repeatedly shown, a redistribution of wealth and income is unlikely to occur without major social upheavals (and these often lead, in turn, to a reestablishment of similar structures only with different occupants).

In conclusion, the reduction of per capita affluence to sustainable levels is not so much a scientific or technical problem but rather a socio-political challenge. In order to avoid catastrophe, it will be necessary to convince those who control and guide our society that they, as others in previous cultures now extinct, will not be able to escape the consequences of global environmental and societal collapse (Diamond, 2005; Tainter, 1988; Wright 2004). It therefore will be in their enlightened self-interest to take steps towards a more just, equitable, and sustainable world.

---

[11] The average individual income of the global top 20% is around 150 times larger than the bottom 20%. Similarly, the net worth of a few hundred billionaires is equal to the combined "wealth" (or lack thereof) of more than 2 billion of the world's poorest people (Korten, 1995).

7 Conclusions

Society will move towards sustainability if total impact (I), expressed either in terms of energy and materials use or pollution, declines with time, i.e., $dI/dt < 0$. Conversely, society will approach collapse if $dI/dt > 0$. The traditional interpretation of the IPAT Eq. 1a reflects the optimistic view that technological innovations, particularly eco-efficiency improvements, will significantly reduce the T-factor, thereby causing a corresponding decline in impact (I). Unfortunately, as was demonstrated in the above analyses, progress in science and technology has not only improved efficiencies but at the same time has increased both consumer population size (P) and per-capita affluence (A). As a result, total impact, such as energy, mineral, and land-use as well as CO_2 emissions, have in most cases not declined but increased with time, indicating that industrial society is still moving towards collapse. Clearly, the belief that more science and technology, as currently practiced, will automatically result in sustainability and avert collapse is greatly mistaken. Better science and technology will certainly be necessary but alone will be insufficient for bringing about sustainability. What is required and is indeed absolutely essential is a change in societal values and policies to consciously direct technological innovation towards the goal of decreasing total impact.

The importance of society's goals and values in terms of directing technological change was made clear by Meadows et al. (2004):

> "One reason technology and markets are unlikely to prevent over-shoot and collapse is that technology and markets are merely tools to serve the goals of society as a whole. If society's implicit goals are to exploit nature, enrich the elites, and ignore the long-term, then society will develop technologies and markets that destroy the environment, widen the gap between rich and poor, and optimize the short term. In short, society develops technologies and markets that hasten a collapse instead of preventing it (p. 8).... Technology and markets typically serve the most powerful segments of society. If the primary goal is growth, they produce growth as long as they can. If the primary goals were equity and sustainability, they could also serve those goals (p. 234)."

In short, without a significant change in society's values, the current direction of progress in science and technology will only implement the existing values of growth, exploitation, and inequality, thereby accelerating our approach to collapse. Consequently, the main challenge will be to change society's goals from growth to material sufficiency (i.e., steady-state economy) and stabilized population size; from exploitation to just treatment of labor, future generations, and the environment; and from gross inequality to a more fair distribution of both income and wealth. These changes in societal values would then automatically translate into various policies which redirect science and technology towards meeting these new goals.

As the above analyses have shown, there is no shortage of potential policies to promote sustainability, such as (a) halting population growth via comprehensive population stabilization plans and better access to birth control methods, (b) reducing total matter-energy throughput and pollution by removing perverse subsidies, enacting regulations that limit waste discharges and the depletion of non-renewable resources, and implementing ecological tax reform, and (c) transitioning towards a steady-state economy where per-capita affluence is stabilized at lower levels by replacing wasteful conspicuous material consumption with increased non-material rewards, thereby enhancing subjective well-being. Similarly, there are significant potential contributions which science and technology can make to help implement these sustainability policies, such as (a) using electronic mass media to change cultural norms towards smaller family size and developing less costly and user-friendly birth control methods, (b) improving the efficiencies of materials and energy use and designing clean, eco-efficient industrial processes, and (c) conducting research on the non-materialistic sources of subjective well-being and developing, as well as promoting via the electronic media, various green consumption alternatives. In fact, many technologies, some of them rather simple, already exist with which to promote sustainability (Trainer, 1995) but they are not implemented on a large scale because they do not advance the current dominant goals of growth, exploitation, and inequality. Again, the most important step towards avoiding societal collapse is a fundamental change in values. Without this first step, there will be no policies to guide technological change in the direction of sustainability, and the current direction of progress in science and technology will hasten collapse rather than prevent it.

Unfortunately, there is very little time left for the required value changes to occur. Indeed, all unstable scenarios that were simulated by Meadows et al. (2004) using their World3 model predicted collapse within the next 100 years. And, as the same authors have shown, the longer we wait to change direction, the fewer choices for action we will have. While it is probably true that resistance to value change is present at all levels of society, the strongest opposition is expected to come from those who benefit most from the current economic system. In earlier cultures now extinct, such individuals and groups also believed that they could isolate themselves from the consequences of their unsustainable actions (Diamond, 2005; Wright, 2004). Clearly, they were dead wrong. They and their entire societies descended into social and political chaos with a precipitous rise in death rates and the disintegration of infrastructure, traditions, and accumulated knowledge (Tainter, 1988). Probably the most important step towards preventing the collapse of our technological society is to convince those who exert the greatest influence that it is in their own best interests to promote the necessary value changes.

8 Disclaimer

The views expressed in this article are solely those of the authors and do not necessarily reflect the official position of Battelle Memorial Institute, Pacific Northwest National Laboratory, or the U.S. Department of Energy.

References

Abramovitz, M. (1956). Resource and output trends in the United States since 1870. *American Economic Review Papers and Proceedings, 46*(May), 5–23.

Adriaanse, A. et al. (1997). *Resource flows the material basis of industrial economies*. Washington, DC: World Resources Institute.

Alfredsson, E. C. (2004). Green consumption—no solution for climate change. *Energy, 29*, 513–524.

Argyle, M. (1987). *The psychology of happiness*. London: Methuen.

Ausubel, J. H. (1996). Can technology spare the earth? *American Scientist, 84*, 166–178, March–April Issue.

Ausubel, J. H., & Gruebler, A. (1995). Working less and living longer: Long-term trends in working time and time budgets. *Technological Forecasting and Social Change, 50*, 113–131.

Ayres, R. U., & van den Bergh, C. J. M. (2005). A theory of economic growth with material/energy resources and dematerialization: Interaction of three growth mechanisms. *Ecological Economics, 55*, 96–118.

Ayres, R. U., & Warr, B. (2005). Accounting for growth: The role of physical work. *Structural Change and Economic Dynamics, 16*, 181–209.

Balzhiser, R. E., Samuels, M. R., & Elisassen, J. D. (1972). *Chemical engineering thermodynamics—the study of energy, entropy, and equilibrium*. Englewood Cliffs, New Jersey: Prentice-Hall.

Barnard, N. D., Nicholson, A., & Howard, J. L. (1995). The medical costs attributable to meat consumption. *Preventative Medicine, 24*(6), 646–655.

Beaudreau, B. C. (2005). Engineering and economic growth. *Structural Change and Economic Dynamics, 16*, 211–220.

Beckerman, W. (1996) *Through green-colored glasses: Environmentalism reconsidered*. Washington, DC: Cato Institute.

Bender, W. H. (1994). An end use analysis of global food requirements. *Food Policy, 19*(4), 381–395.

Bentzen, J. (2004). Estimating the rebound effect in US manufacturing energy consumption. *Energy Economics, 26*, 123–134.

Betts, K. (2004). Calculating computing's environmental cost. *Environmental Science and Technology*, November 15 Issue, 432A–433A.

Binswanger, M. (2001). Technological progress and sustainable development: What about the rebound effect? *Ecological Economics, 36*, 119–132.

Birdsall, N. (1994). Another look at population and global warming. In *Population, environment, and development*. Proceedings of the United Nations Expert Group Meeting on Population, Environment, and Development held at the United Nations Headquarters, 20–24 January 1992, New York, United Nations, pp. 39–54.

Birol, F., & Keppler, J. H. (2000). Prices, technology development and the rebound effect. *Energy Policy, 28*, 457–469.

Blair, R. D., Kaserman, D. & Tepel, R. C. (1984). The impact of improved mileage on gasoline consumption. *Economic Inquiry, 22*, 209–217.

Bongaarts, J. (1992). Population growth and global warming. *Population and Development Review, 18*(2), 299–319.

Bongaarts, J., O'Neill, B. C. & Gaffin, S. R. (1997). Global warming policy: Population left out of in the cold. *Environment, 39*(9), 40–41.

Braun, E. (1995). *Futile progress: Technology's empty promise*. London, UK: Earthscan Publications.

Brookes, L. (2000). Energy efficiency fallacies revisited. *Energy Policy, 28*, 355–366.

Campbell C. J., & Laherrere, J. H. (1998). The end of cheap oil. *Scientific American, March*, 78–83.

Carlsson-Kanyama, A. (1998). Climate change and dietary choices—how can emissions of greenhouse gases from food consumption be reduced? *Food Policy, 23*(3/4), 277–293.

Castaneda, B. (1997). *An index of sustainable economic welfare for Chile, institute for ecological economics*. Maryland: Solmons.

Cavanagh, J., & Mander, J. (2002). *Alternatives to economic globalization* (1st ed.). San Francisco, CA: Berrett-Koehler Publishers.

Chalkley, A. M., Billett, E., & Harrison, D. (2001). An investigation of the possible extent of the re-spending rebound effect in the sphere of consumer products. *The Journal of Sustainable Product Design, 1*, 163–170.

Chertow, M. R. (2001). The IPAT equation and its variants, *Journal of Industrial Ecology, 4*(4), 13–29.

Cleveland, C. J., & Ruth, M. (1997). When, Where and by How much does thermodynamics constrain economic processes? A survey of Nicholas Georgescu-Roegen's contribution to ecological economics. *Ecological Economics, 22*, 203–223.

Cleveland, C. J., & Ruth, M. (1999). Indicators of dematerialization and the materials intensity of use, *Journal of Industrial Ecology, 2*, 15–50.

Connelly, L., & Koshland, C. P. (1997). Two aspects of consumption: Using an exergy-based measure of degradation to advance the theory and implementation of industrial ecology, *Resource Conservation and Recycling, 19*, 199–217.

Cooper, T. (2005). Slower consumption: Reflections on product life spans and the 'Throwaway Society'. *Journal of Industrial Ecology, 9*(1–2), 51–67.

Daly, H. E. (1980). The steady-state economy: toward a political economy of biophysical equilibrium and moral growth. In H. E. Daly (Ed.), *Economics, ecology, ethics—assays toward a steady-state economy*. New York: W.H. Freedman.

Daly, H. E., & Cobb, J. (1989). *For the common good—redirecting the economy towards community, the environment, and sustainable development*. London, UK: Green Print.

Deevey, E. S. (1960). The human population. *Scientific American, 203*, 195–204.

Denison, E. F. (1985). *Trends in American economic growth: 1929–1982*. Washington, DC: Brookings Institution.

Diamond, J. (2005). *Collapse: How societies choose to fail or succeed*. New York, NY: Viking Penguin.

Diefenbacher, H. (1994). The ISEW in Germany. In C. Cobb & J. Cobb (Eds.), *The green national product*. Lanham, Maryland: University of Americas Press.

Diener, E., & Oishi, S. (2000). Money and happiness: Income and subjective well-being across nations. In E. Diener, & E. M. Suh (Eds.), *Culture and subjective well-being*. Cambridge, Massachusetts: MIT Press, pp. 185–218.

Dresner, S. (2002). *The principles of sustainability*. London, UK: Earthscan Publications.

Duchin, F. (2005). Sustainable consumption of food. *Journal of Industrial Ecology, 9*(1–2), 99–113.

Dohmen, F., & Hornig, F. (2004). Der Windmuehlen Wahn—Die Grosse Luftnummer (The Windmill Craze – The Great Air Number). *Der Spiegel, 14*, 80–97.

Durning, A. T. (1992). *How much is enough? The consumer society and the future of the earth*. New York: W.W. Norton.

Ehrlich, P. R. (1989). The limits to substitution: Meta-resource depletion and a new economic-ecological paradigm. *Ecological Economics, 1*, 9–16.

Ehrlich, P. R., & Ehrlich, A. H. (1991). *The population explosion*. Touchstone Books.

Ehrlich, P. R., & Holdren, J. (1971). Impact of population growth. *Science, 171*, 1212–1217.

Elliott, D. L., Wendell, L. L., & Gower, G. L. (1992). Wind energy potential in the united states considering environmental and land-use exclusions. In M. E. Ardan, S. M. A. Burley & M. Coleman (Eds.), *Proceedings of the biennial congress of the international solar energy society*, Solar World Congress in Denver, Colorado, Oxford, UK, Pergamon, Vol. 1(2), pp. 576–581.

Faber, M., Niemes, H. & Stephan, G. (1995). *Entropy, environment, and resources*. Berlin, Germany: Spinger Verlag.

Fabricant, S. (1954). Economic progress and economic change, *34th Annual report of the National Bureau of Economic Research*, New York.

Frank, R. H. (1999). *Luxury fever—Why money fails to satisfy in an era of excess*. New York: The Free Press.

Frey, B. S., & Stutzer, A. (2000). Happiness, economy, and institutions. *Economics Journal, 110*(446), 918–938.

Frey, B. S., & Stutzer, A. (2002). What can economists learn from happiness research? *Journal of Economic Literature, 40*, 402–435.

Gaffin, S. R. (1998). World population projections for greenhouse gas emission scenarios. *Mitigation and Adaptation Strategies for Global Change, 3*, 133–170.

Gerbens-Leenes, P. W., & Nonhebel, S. (2002). Consumption patterns and their effects on land required for food. *Ecological Economics, 42*, 185–199.

Glasby, G. P. (1988). Entropy, pollution and environmental degradation. *Ambio, 17*, 330–335.

Goodland, R. (1997). Environmental sustainability in agriculture: Diet matters, *Ecological Economics, 23*(3), 189–200.

Graedel, T. E., & Allenby, B. R. (1995). *Industrial ecology*. Englewood Cliffs, NJ: Prentice Hall.

Greene, D. L. (1992). Vehicle use and fuel economy: How big is the rebound effect? *The Energy Journal, 13*(1), 117–143.

Greening, L. A., Greene, D. L. & Difiglio, C. (2000). Energy efficiency and consumption—the rebound effect—a survey. *Energy Policy, 28*, 389–401.

Grubb, M. J. (1990). Energy efficiency and economic fallacies. *Energy Policy*, October Issue, pp. 783–785.

Gruebler, A. (1994). Industrialization as a historical phenomenon. *Industrial Ecology and Global Change*, pp. 43–68.

Gutes, M. C. (1996). The concept of weak sustainability. *Ecological Economics, 17*, 147–156.

Haas, R., & Biermayr, P. (2000). The rebound effect for space heating: Empirical evidence from Austria. *Energy Policy, 28*, 403–410.

Hamilton, C. (2003). *Growth fetish*. NSW Australia: Allen and Unwin, Crows Nest.

Hannon, B. (1975). Energy conservation and the consumer. *Science, 189*(4197), 95–102.

Herring, H. (1999). Does energy efficiency save energy? The debate and its consequences. *Applied Energy, 63*, 209–226.

Hertwich, E. G. (2005). Consumption and the rebound effect: An industrial ecology perspective. *Journal of Industrial Ecology, 9*(1–2), 85–98.

Hobbs, F., & Stoops, N. (2002). Demographic trends in the 20th century, U.S. Census Bureau, Census 2000 Special Reports, Series CENSR-4, U.S. Government Printing Office, Washington, DC, www.census.gov/prod/2002pubs/CENSR-4.pdf.

Holdren, J. P. (1991). Population and the energy problem. *Population and Environment, 12*(3), 231–255.

Howarth, R. (1997). Energy efficiency and economic growth. *Contemporary Economic Policy, 15*, 1–8.

Huesemann, M. H. (2001). Can pollution problems be effectively solved by environmental science and technology? An analysis of critical limitations. *Ecological Economics, 37*, 271–287.

Huesemann, M. H. (2003). The limits of technological solutions to sustainable development. *Clean Technology and Environmental Policy, 5*, 21–34.

Huesemann, M. H. (2006). Can advances in science and technology prevent global warming? A critical review of limitations and challenges. *Mitigation and Adaptation for Global Change, 11*, 539–577.

Inhaber, H., & Saunders, H. (1994). Road to nowhere: Energy conservation often backfires and leads to increased consumption. *The Sciences, 34*(6), 20–25.

Intergovernmental Panel on Climate Change (IPCC). (2001). *Special report on emission scenarios*, www.ipcc.ch.

International Center for Technology Assessment (ICTA). (1998). The real price of gasoline, report no. 3: An analysis of the hidden external costs consumers pay to fuel their automobiles, www.icta.org/doc/Real%20Price%20of%20Gasoline.pdf.

Jackson, T. (2005). Live better by consuming less? Is there a 'double dividend' in sustainable consumption? *Journal of Industrial Ecology, 9*(1–2), 19–36.

Jackson, T., & Marks, N. (1999). Consumption, sustainable welfare and human needs—with reference to UK expenditure patterns between 1954 and 1994. *Ecological Economics, 28*, 421–441.

Jackson, T., & Stymne, S. (1996). *Sustainable economic welfare in Sweden—a pilot index 1950–1992*. Stockholm, Sweden: Stockholm Environment Institute.

Jevons, W. S., (1906). *The coal question: Can Britain survive?* First published in 1865. London, UK: Republished by Macmillan.

Jobling, M. A., Hurles, M. E., & Tyler-Smith, C. (2003). *Human evolutionary genetics: Origin, peoples and disease*, Garland Science/Francis and Taylor Group.

Jochem, E. (2000). Energy and end-use efficiency. In J. Goldemberg (Ed.), W*orld energy assessment: Energy and the challenge of sustainability* (pp. 174–217). Chapter 6, United Nations Development Programme, United Nations Department of Economic and Social Affairs, World Energy Council.

Kahnemann, D., & Tversky, A. (1984). Choices, values and frames. *American Psychologist, 39*, 341–350.

Kasser, T., (2002). *The high price of materialism*. Cambridge, Massachusetts: MIT Press.

Keeling, C. D., & Whorf, T. P. Atmospheric CO_2 concentrations (up to 2003)—Mauna Loa Observatory, Hawaii, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, http://mercury.ornl.gov/cdiac.

Kendrick, J. W. (1961). *Productivity trends in the United States*. New York: Princeton University Press (for the National Bureau of Economic Research).

Khazzoom, J. D. (1980). Economic implications of mandated efficiency standards for household appliances. *Energy Journal, 1*(4), 21–40.

Khazzoom, J. D. (1987). Energy saving resulting from the adoption of more efficient appliances. *Energy Journal, 8*(4), 85–89.

Khazzoom, J. D. (1989). Energy savings from more efficient appliances: A rejoinder. *Energy Journal, 10*(1), 157–166.

Kheshgi, H. S., Prince, R. C. & Marland, G. (2000). The potential of biomass fuels in the context of global climate change: Focus on transportation fuels'. *Annual Review Energy Environment, 25*, 199–244.

Kivel, P. (2004). *You call this a democracy? Who benefits, who pays and who really decides*. New York: The Apex Press.

Korten, D. (1995). *When corporations rule the world*. Berrett-Koehler Publishers.

Kramer, K. J., Moll, H. C., Nonhebel, S. & Wilting, H. C. (1999). Greenhouse gas emissions related to Dutch food consumption. *Energy Policy, 27*, 203–216.

Laitner, J. A. (2000). Energy efficiency: Rebounding to a sound analytical perspective. *Energy Policy, 28*, 471–475.

Lane, R. E. (2001). *The loss of happiness in market democracies*. New Haven, Connecticut: Yale University Press.

Lovins, A. B. (1988). Energy saving resulting from the adoption of more efficient appliances: Another view. *Energy Journal, 9*(2), 155–162.

Maddison, A. (1991). Dynamic forces in capitalist development: A long-run comparative view, Oxford University Press.

Mander, J. (1978). Four arguments for the elimination of television, Harper Perennial.

Marland, G., Boden, T. A., & Andres, R. J. (2002). Global, regional, and national fossil fuel CO_2 emissions (up to 2002), Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, http://mercury.ornl.gov/cdiac.

McDonough, W., & Braungart, M. (2002). *Cradle to cradle: Remaking the way we make things*. North Point Press.

McKeown, T. (1988). *The origins of human disease*. New York: Basil Blackwell, Inc.

Meadows, D., Randers, J. & Meadows, D. (2004). *Limits to growth the 30-year update*. White River Junction, Vermont: Chelsea Green Publishing Company.

Myers, D. G., & Diener, E. (1996). The pursuit of happiness. *Scientific American, 274*(5), 70–72.

Myers, N., & Kent, J. (2001). *Perverse subsidies: How misused tax dollars harm the environment and the economy*. Washington, DC: Island Press.

Myers, N. (2003). Consumption: Challenge to sustainable development. *Science, 276*, 53–55.

Nakicenovic, N. (1996). Freeing energy from carbon. *Daedalus, 125*(3), 95–112.

Nakicenovic, N., & Gruebler, A. (1993). Energy conversion, conservation, and efficiency, chapter 2. *Energy, 18*(5), 421–435.

Nakicenovic, N., Gruebler, A. & McDonald, A. (1998). *Global energy perspective*. Cambridge, UK: Cambridge University Press.

Nelson, D. L, & Cox, M. M. (2005). *Lehninger principles of biochemistry* (4th ed.). New York: W.H. Freeman and Company.

O'Connor, M. (1994). Entropy, liberty, and catastrophe: The physics and metaphysics of waste disposal, In P. Burley & J. Foster (Eds.), *Economics and thermodynamics: New perspectives on economic analysis*. Boston, Mass: Kluwer, pp. 119–182.

OECD/IEA. (2004). *30 Years of energy use in IEA countries.* Paris, France: International Energy Agency (IEA).

O'Neill, B. C., MacKellar, F. L. & Lutz, W. (2001). *Population and climate change*. New York: Cambridge University Press.

Oswald, A. J. (1997). Happiness and economic performance. *Economic Journal, 107*(445), 1815–1831.

Pimentel, D., & Pimentel, M. (1996). *Food, energy, and society*. Boulder, Colorado: University of Colorado Press.

Pritchett, L. H. (1994). Desired fertility and the impact of population policies. *Population and Development Review, 20*(1), 1–55.

Rees, W. E., & Wackernagel, M. (1995). *Our ecological footprint: Reducing environmental impact on the earth*. Gabriola Island, British Columbia, Canada: New Society Publishers.

Romm, J. J., & Curtis, C. B. (1996). Mideast oil forever? *Atlantic Monthly, 277*(4), 57.

Roy, J. (2000). The rebound effect: Some empirical evidence from india. *Energy Policy, 28*, 433–438.

Ruth, M. (1993). *Integrating economics, ecology and thermodynamics*. Dortrecht, The Netherlands: Kluwer.

Ruth, M. (1995). Information, order and knowledge in economic and ecological systems: Implications for material and energy use. *Ecological Economics, 13*, 99–114.

Ryerson, W.N., (1995). Sixteen myths about population. *Focus, 5*(1), Population Media Center, http://www.populationmedia.org/issues/sixteen_myths/myths.html.

Salter, W. E. G. (1960). *Productivity and technical change*. London, UK: Cambridge University Press.

Samuelson, P. A., & Nordhaus, W. D. (1989). *Economics*, 13th ed. New York, NY: McGraw-Hill.

Sanne, C. (2000). Dealing with environmental savings in a dynamical economy—how to stop chasing your tail in the pursuit of sustainability. *Energy Policy, 28*, 487–495.

Saunders, H. D. (1992). The Khazzoom-Brookes postulate and Neoclassical growth. *Energy Journal, 13*(4), 131–148.

Saunders, H. D. (2000). A view from the macro side: Rebound, backfire, and Khazzoom-Brookes. *Energy Policy, 28*, 439–449.

Schipper, L., & Grubb, M. (2000). On the rebound? Feedback between energy intensities and energy uses in IEA countries. *Energy Policy, 28*, 367–388.

Schor, J. B. (2005). Sustainable consumption and worktime reduction. *Journal of Industrial Ecology, 9*(1–2), 37–50.

Schor, J. B. (1992). *The overworked American: The unexpected decline of leisure time*. New York: Basic Books.

Schurr, S. (1982). Energy efficiency and productive efficiency: Some thoughts based on american experience. *Energy Journal, 3*(3), 3–14.

Schumpeter, J. (1934). *The theory of economic development*. Cambridge, MA: Harvard University Press.

Sieferle, R. P. (2004). Sustainability in a world history perspective, In B. Benzing & B. Hermann (Eds.), *Exploitation and overexploitation in societies past and present*. Muenster: Lit Verlag, pp. 123–141.

Simon, J. L. (1996). *The ultimate resource 2*. Princeton, New Jersey: Princeton University Press.

Solow, R. M. (1957). Technical change and the aggregate production function. *Review of Economics and Statistics, 39*(August), 312–320.

Stockhammer, E., Hochreiter, H., Obermayr, B., & Steiner, K. (1997). The Index of Sustainable Economic Welfare (ISEW) as an alternative to GDP in measuring economic welfare. The results of the Austrian ISEW calculation 1955–1992. *Ecological Economics, 21*(1), 19–34.

Tainter, J. A. (1988). *The collapse of complex societies*. Cambridge UK: Cambridge University Press.

The Population Council. (1992). Future population growth and global warming. In *Population, environment, and development*, Proceedings of the United Nations Expert Group Meeting on Population, Environment, and Development held at the United National Headquarters, 20–24 January 1992, New York, United Nations, pp. 280–285.

Trainer, T. (1995). *The conserver society: Alternatives for sustainability*. London, UK: Zed Books.

U.S. Department of Agriculture (USDA). (2005). National Agricultural Statistics Service, Crops by State, http://usda.mannlib.cornell.edu/data-sets/crops/95111/.

U.S. Department of Energy (DOE). (2003). Energy information administration. *Emissions of Greenhouse Gases in the United States 2003, Trends in U.S. Carbon Intensity and Total Greenhouse Gas Intensity*, www.eia.doe.gov/oiaf/1605/ggrpt/trends.html.

U.S. Department of Energy (DOE). (2004). Energy information administration. *Energy Overview*, http://www.eia.doe.gov/emeu/mer/overview.html.

U.S. Office of Management and Budget (OMB). (2004). Budget of the United States Government, Fiscal Year 2004, Historical Tables, Table 10.1, pp. 182–183, http://www.whitehouse.gov/omb/budget.

Vollebergh, H. R. J., & Kemfert, C. (2005). The role of technological change for a sustainable development. *Ecological Economics, 54*, 133–147.

Von Weizsacker, E., Lovins, A. B., & Lovins, L. H. (1998). *Factor four: Doubling wealth—halfing resource use*. London: Earthscan Publications Ltd.

Weeks, J., (1992). How to influence fertility: The experience so far. In L. Grant (Ed.), *Elephants in the Volkswagen: Facing the tough questions about our overcrowded country* (pp. 178–196), Chapter 15. New York: W.H. Freeman.

Williams, E., Ayres, R. U., & Heller, M. (2002). The 1.7 kilogram microchip: Energy and material use in the production of semiconductor devices. *Environmental Science and Technology, 36*(24), 5504–5510.

Williams, E. (2004). Energy intensity of computer manufacturing: Hybrid assessment combining process and economic input-output methods. *Environmental Science and Technology, 38*(22), 6166–6174.

Wright, R. (2004). *A short history of progress*. New York: Carroll and Graf Publishers.