Original paper

Clean Techn Environ Policy 5 (2003) 21–34
DOI 10.1007/s10098-002-0173-8

The limits of technological solutions to sustainable development

M.H. Huesemann

Abstract Sustainable development has been defined by political and corporate leaders as the combination of environmental protection and economic growth. As a result, the concept of eco-efficiency has been promoted as the primary tool for achieving industrial sustainability. However, there are at least four reasons why technological improvements in eco-efficiency alone will be insufficient to bring about a transition to sustainability. First, considering that the very foundations of western industrial societies are based on the exploitation of non-renewable minerals and fuels, it will be extremely difficult to switch to an industrial and economic system based solely on renewable resources. Clearly, the continuing use of non-renewables is inherently unsustainable because of finite material supplies and the fact that 100% recycling is impossible. Second, given the limited supply of non-renewable fuels, long-term sustainability can only be guaranteed if all energy is derived directly or indirectly from the sun. However, if the current U.S. energy demand would have to be supplied solely from solar sources, a wide range of serious and unavoidable negative environmental impacts are likely to result. Third, even the best of human ingenuity and the greatest technological optimism are bounded by the second law of thermodynamics, which dictates that all industrial and economic activities have unavoidable negative environmental consequences. Finally, improvements in eco-efficiency alone will not guarantee a reduction in the total environmental impact if economic growth is allowed to continue. Unless growth in both population and consumption is restrained, these technological improvements only delay the onset of negative consequences that, as a result, will have increased in severity, thereby reducing our freedom to choose satisfying solutions.

Introduction

The term "sustainable development" has received unprecedented popularity ever since it was first defined by the World Commission on Environment and Development more than 10 years ago. In its famed Brundtland report, sustainable development was to "ensure that humanity meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987, p. 9). Unfortunately, in order to reach an agreement among widely disparate parties, the concept of sustainable development was kept deliberately vague and inherently self-contradictory which resulted in the situation where, in the words of ecologist David Reid, "endless streams of academics and diplomats could spend many comfortable hours trying to define it without success." (Reid 1995, p. 212)

Within a few years after publication of the Brundtland report, however, the international business community stepped forward and took the opportunity to come up with a more concrete definition of this rather fuzzy term. They envisioned sustainable development to be a combination of continued economic growth and environmental protection. For example, the International Chamber of Commerce stated that "sustainable development combines environmental protection with economic growth and development" (Welford 1997, p. 69). Similarly, the Business Council for Sustainable Development, under the leadership of the Swiss millionaire industrialist Stephan Schmidheiny, agreed that "sustainable development combines the objectives of growth with environmental protection for a better future" (Welford 1997, p. 75). In the U.S., the President's Council on Sustainable Development also believes that "it is essential to seek economic prosperity, environmental protection, and social equity together (PCSD 1996, p. 1)." Similarly, the European Organization for Economic Cooperation and Development (OECD) issued a major report on eco-efficiency in an effort to promote "sustainable" economic growth (OECD 1998).

In order to ensure that continued economic growth and environmental protection can go hand in hand, business leaders promoted the concept of "eco-efficiency" as the primary tool for achieving industrial sustainability. In fact, the Business Council for Sustainable Development originally coined the term eco-efficiency and defined it as "adding maximum value with minimum resource use and minimum pollution." (Welford 1997, p. 79). Or, more specifically in the words of Stephan Schmidheiny: "Corporations that achieve ever more efficiency while preventing pollution through good housekeeping, materials substitution, cleaner technologies, and cleaner products and that strive for more efficient use and

Received: 16 August 2002 / Accepted: 29 October 2002
Published online: 14 December 2002

M.H. Huesemann
Marine Science Laboratory, Pacific Northwest National Laboratory, 1529 West Sequim Bay Road, 98382 Sequim, WA, USA
E-mail: michael.huesemann@pnl.gov
Tel.: +1-360-6813618
Fax: +1-360-6813699

recovery of resources can be called “eco-efficient.” (Schmidheiny 1992, p. xii). The Business Council for Sustainable Development also suggested that eco-efficiency should be the main corporate response to the goal of sustainable development (Welford 1997, DeSimone and Popoff 1997).

In short, the complex societal challenge of sustainable development was reduced to the purely technical problem of improving industrial eco-efficiency or “producing more with less” (World Commission on Environment and Development, 1987, p. 206). It is the objective of this paper to show that improvements in eco-efficiency alone cannot guarantee sustainability of current western industrial societies. However, before addressing four specific inherent technological limits to sustainable development, we will briefly review how eco-efficiency is thought to ensure the sustainability of industrialized civilizations.

In search of sustainability: eco-efficiency and industrial ecology

Despite the rather vague definition of the term “sustainable development” by the World Commission on Environment and Development, both economists and ecologists have attempted to provide a clear set of sustainability criteria. Unfortunately, no consensus has been achieved and two contrasting viewpoints have emerged. One view held by many economists is that “weak sustainability” is sufficient (Pearce and Atkinson 1993, Gutes 1996, Renning and Wiggering 1997). According to the weak sustainability criterion, depletion of natural resources is acceptable as long as the aggregate stock of manufactured and natural assets is not decreasing, i.e., human made capital is used as a substitute for depleted natural capital (Rees and Wackernagel 1995). This viewpoint is opposed by many biologists and environmentally minded economists who assert that natural capital stocks need to be held constant independent of human capital in order to guarantee (strong) sustainability (Constanza and Daly 1992). Given the fact that human capital cannot indefinitely substitute for an ever declining stock of natural resources, it is clear that “strong” rather than “weak” sustainability is necessary to ensure that current economic activities can continue without serious interruptions at least in theory ad infinitum[1]. In fact, only two general conditions need to be satisfied to ensure “strong” sustainability over the long run (Daly 1980, Kuik and Verbruggen 1991, O’Riodan 1993, Constanza and Patten 1995, Ayres 1996, Azar et al. 1996, Daly 1996, Gutes 1996, Renning and Wiggering 1997, Hueting and Reijnders 1998):

1. All raw materials used in industrial processes as well as all energy must be supplied from renewable resources at rates that do not exceed the regenerative capacity of the respective eco-system (sustainable yield) and do not cause any other disruptive environmental side-effects.
2. Wastes can only be released into the environment at a rate compatible with the assimilation capacity of the respective eco-system.

The first sustainability condition assures the long-term supply of material and energy inputs that are extracted from the environment to run industrial economies. Considering that the quantities of any non-renewable resources such as minerals and fossil fuels are inherently limited, it is clear that the exploitation of these non-renewables is by definition short-lived and therefore not sustainable. However, as mentioned above, it has been argued by certain economists (Pierce and Atkinson 1993, Gutes 1996, Renning and Wiggering 1997) that it may be permissible to use non-renewable resources as long as renewable substitutes can be identified. For example, according to this “weak” sustainability hypothesis, it is acceptable to use up a given stock of fossil fuel energy if an identical amount of renewable energy is captured and stored for later use (e.g., by growing trees to compensate for burning coal). Nevertheless, since the stock of non-renewables will ultimately be depleted it is clear that this substitution process cannot continue ad infinitum and therefore is inherently not sustainable. Similarly, the argument made by technological optimists like Sagoff (1995) and Ausubel (1996) that other non-renewable substitutes (e.g., natural gas for coal, petroleum-based plastics for aluminum, etc.) can be found is also flawed and short-sighted since the supplies of *any* non-renewables are, by definition, limited (Skinner 1987, Ehrlich 1989, Youngquist 1997). Finally, it has been suggested that the use of non-renewable materials is sustainable as long as they are recycled. However, as will be explored in more detail below, complete recycling is impossible from a practical standpoint. In summary, substitution and recycling strategies only delay the depletion of non-renewable stocks and therefore may buy time in the transition to true or strong sustainability, which ultimately is only guaranteed in an economy based on renewable resources.

The second sustainability condition assures the long-term stability of the environment that ultimately receives all outputs (e.g., wastes) from industrial economies. There are a number of approaches for minimizing the environmental impacts related to industrial activities. First, the generation of waste is minimized by redesigning industrial processes to avoid the formation of undesirable byproducts (i.e., pollution prevention) or by recycling wastes back into the production system so that they never come into contact with ecological receptors. Second, if any waste has to be released into the environment it must be guaranteed that the receiving eco-system can assimilate it without problems. In order to assure this condition, wastes ideally should be non-toxic, readily biodegradable or biologically inert, and should be released at a rate that does not cause harmful eco-system disturbances.

These different sustainability principles form the basis of “industrial ecology”, the newly formed “science of sustainability” (Allenby 1999, p. xi), whose primary mis-

[1] It is clear from historical evidence that all civilizations and cultures have only a limited life span (Tainter 1988). Nevertheless, the two sustainability conditions probably need to be satisfied merely to assure the continued existence of industrial societies for the next hundred years. In addition, the “ad infinitum” time horizon forces one to think about all potential consequences of present economic activities and to design sustainability criteria that do not transfer costs into the distant future.

sion is to improve the eco-efficiency of current industrial systems (Allenby and Richard, 1994, Ayres and Simonis 1994, Graedel and Allenby 1995, Ayres and Ayres 1996, DeSimone and Popoff 1997, Allenby 1999). As shown in Fig. 1, current economic activities are unsustainable for at least three major reasons. First, more than 90% of the energy that drives the U.S. economy is derived from non-renewable fossil fuels whose combustion byproducts such as CO_2, SO_2, NO_x, and particulates cause widespread air pollution and global warming (Pimentel et al. 1994, Houghton 1997). Second, almost all raw material inputs to the economy consist of non-renewable minerals and metals. For example, each U.S. citizen uses per year on average 338 lb (153 kg) phosphate rock, 1,140 lb (517 kg) iron and steel, 49 lb (22 kg) aluminum, 21 lb (9.5 kg) copper, 14 lb (6.3 kg) lead and many other trace minerals and metals (Youngquist 1997, p. 24). The third reason is related to the fact that most materials flow in a *linear* fashion through the economy (Fig. 1A). Natural resources are extracted from the environment and refined into raw materials that are then manufactured into consumer products. After consumption, the resulting wastes are returned to the environment where they often cause serious deterioration in the receiving ecosystems.

In order to avoid the numerous negative impacts associated with the dispersal of wastes into the environment, industrial ecologists have focused to date most of their attention on "closing the materials cycle" (Graedel and Allenby 1995, Ayres and Ayres 1996, Allenby 1999). As shown in Fig. 1B, it may in theory be possible to isolate the economy almost completely from the environment by recycling all wastes into materials that can then again be manufactured into consumer products. If certain waste materials cannot be recycled but have to be released into the environment, it may also be possible to redesign industrial processes and systems in such a way to assure that wastes are compatible with the absorption capacity of the receiving eco-system and therefore cause only minimal environmental disturbance. For example, in the last decade, industrial ecologists have developed a wide range of protocols and procedures for pollution prevention, recycling, life-cycle analysis, design for environment, green chemistry, and related topics with the overall goal of reducing the negative environmental impacts, particularly pollution, of current industrial activities.

While these various research activities will no doubt improve the overall eco-efficiency of industrial economies, it is highly questionable whether these technological steps will achieve or *even approach* the desired goal of sustainability (Graedel 2000). There are at least four major reasons for this, all of which will be discussed next.

It is impossible to completely recycle all non-renewable resources

Although the use of non-renewables such as metals and minerals is clearly unsustainable in the long run, industrial

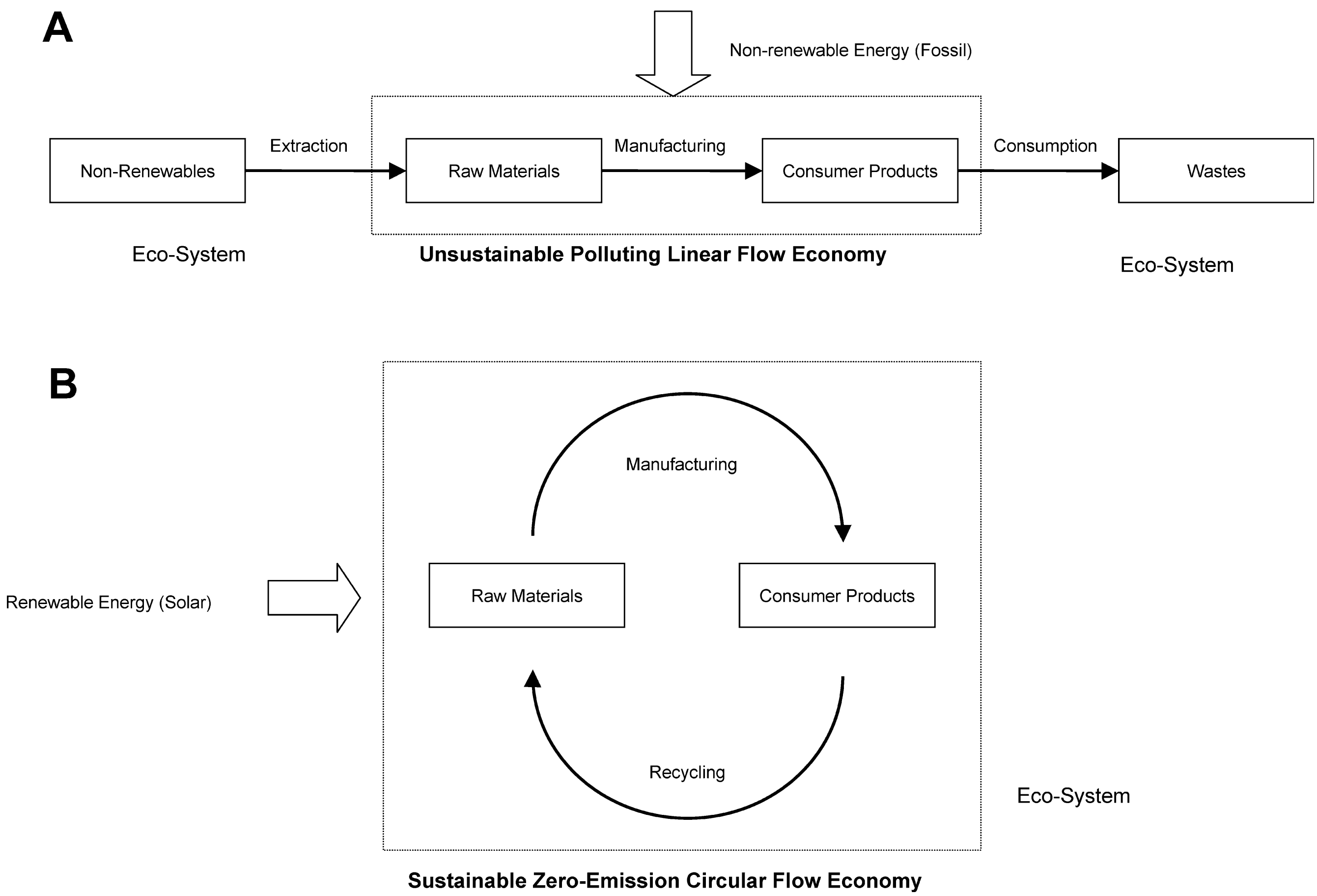

Fig. 1. **A** Present unsustainable polluting linear flow economy. **B** Future sustainable zero-emission circular flow economy

Table 1. Classes of non-renewable resources based ontheir potential for recycling (adopted from Ayres 1994)

Class of non-renewable material	Recycling technically feasible	Recycling economically feasible	Examples
I	Yes	Yes	Most industrial metals and catalysts
II	Yes	No	Packaging materials, refrigerants, solvents, etc.
III	No	No	Coatings, pigments, pesticides, herbicides, germicides, preservatives, flocculants, antifreezes, explosives, propellants, fire-retardants, reagents, detergents, fertilizers, fuels, lubricants, etc.

ecologists and pollution prevention specialists have done very little to develop renewable alternatives that can be used as substitutes for non-renewables[2]. Instead, the main approach has been to extend the current supply of non-renewables by "closing the materials cycle" via recycling and other process modifications.

According to pioneering industrial ecologist Robert Ayres, non-renewables can be grouped into three classes based on their technical and economical potential for recycling (Ayres 1994). As shown in Table 1, it is both technically and economically feasible to recycle non-renewables belonging to class I. For example, recycling rates for scrap metals like aluminum, copper, lead, nickel, iron, and zinc range from around 25% to 50% and therefore could still be improved significantly. While the recycling of class II non-renewables such as packaging materials and solvents is certainly possible from a technical standpoint, there have been very few incentives in the U.S. to do so (e.g., bottle deposits). However, considering the successful implementation of recycling regulations dealing with consumer packaging materials in Germany (Duales System Deutschland AG), it should be in principle possible to recover most of them.

The remaining non-renewables belong to class III, whose recycling potential is problematic from both a technical and an economic perspective. Unfortunately, most non-renewables belong to this category, as indicated by the long list of examples given in Table 1. The current use of these class III materials can be considered inherently dissipative since they disperse widely in the environment and become so diluted that it is impractical to recover them for re-use. For example, how will it ever be possible to recycle the potassium or phosphorus used as agricultural fertilizers, the copper dispersed in fungicides, the lead in widely applied paints, or the zinc oxides that are present in the finely dispersed rubber powder that is abraded from car tires?

It could be conceivably argued by optimistic industrial ecologists that it is at least in principle possible to recycle these highly dispersed materials if new technologies are developed and if enough energy is applied to carry out this purification and recycling process (Bianciardi et al. 1993, Connelly and Koshland 1997, Ayres 1999). Complete (100%) recycling occurs in nature all the time as evidenced by the presence of biogeochemical cycles for carbon, oxygen, nitrogen, phosphorus, and many other elements. The cycling of these elements is carried out via a complex system of biological transformation pathways that are enzymatically catalyzed by microorganisms and plants and driven by solar energy. The problem with the class III materials listed in Table 1 is the fact that no circular biological transformation pathways exist for them in nature and it will be extremely difficult to come up with new solar energy driven biotechnologies to recycle these highly dissipated materials (O'Connor 1994). Even if some type of innovative recycling technologies for these class III compounds could be developed (which is highly questionable), it would take tremendous amounts of energy to carry out the recycling process. Using the second law of thermodynamics, it is possible to estimate the minimum energy requirements for concentrating a highly dispersed non-renewable resource. As expected, the energy needed for purification increases drastically with decreasing material concentrations in the environment. Specifically, the mole-specific energy requirements (ΔE, W s/mol) can be calculated as a function of the resource concentration x_i (mole fraction) according to the following equation[3] (Faber et al. 1995, p. 113):

$$\Delta E = -RT\left\{\ln x_i + \frac{1-x_i}{x_i}\ln(1-x_i)\right\} \tag{1}$$

where R is the ideal gas constant and T is the temperature in kelvins. As shown in Fig. 2, energy requirements sky-rocket as the material concentrations approach the extremely low levels that are typical for highly dispersed metals and minerals. Consequently, it is clear that enormous amounts of energy would be required to collect, purify, and recycle highly dissipative wastes such as those listed as class III in Table 1. Considering the potential negative environmental consequences associated with sustainable (renewable) energy generation, a topic discussed in the next section, it is extremely unlikely that there will ever be enough (cheap) energy available to recycle these highly dispersed non-renewable materials from the environment.

[2] The main reason that substitution of non-renewables with renewables has not occurred to a significant degree is that market prices, which are often kept artificially low by subsidies and cost externalization, currently favor the use of non-renewables over renewables. In order to promote substitution with renewables, economic policies will have to be put in place that, at a minimum, reflect the true cost of non-renewable resources by considering all social and environmental externalities and by eliminating all subsidies to special interests, and that ideally also tax the use of non-renewables to hasten the transition to renewables.

[3] This equation applies only to ideal mixtures. Considering that many minerals are not found in ideal mixtures, this equation should be used only as an approximation under these circumstances.

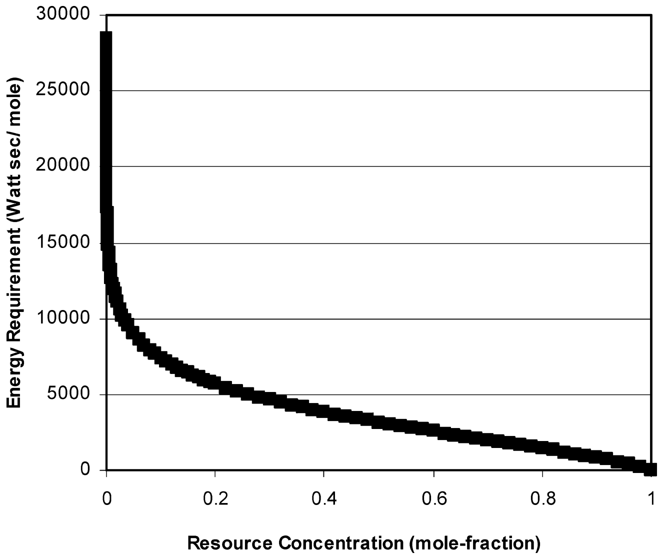

Fig. 2. Relationship between energy requirement and resource concentration at 273 K according to Eq. (1). (based on Fig. 4.5 in Faber et al. 1995)

In summary, the dissipative use of these class III non-renewables poses two major problems for industrial ecologists in that it violates both sustainability conditions outlined above: First, there is only a limited supply of these trace metals and minerals and their costs will increase as high-grade ores become depleted with time (Skinner 1987, Youngquist 1997). Second, and more importantly, the dispersal of these materials is causing major environmental disruption. For example, anthropogenic worldwide atmospheric emissions of arsenic, copper, lead, manganese, mercury, nickel, vanadium, and zinc all significantly exceed the natural (atmospheric) fluxes of these compounds, indicating their likely potential for disturbing natural cycles and disrupting sensitive eco-system functions (Aryes 1994).

In conclusion, the use of non-renewable materials is inherently unsustainable because the materials cycle cannot ever be completely closed and the resulting dispersed materials are likely to cause environmental problems. Improvements in recycling efficiency will only somewhat prolong the limited supply of non-renewables, but this does not in itself guarantee sustainability. It is therefore clear that the goal of true sustainability can only be achieved by eliminating the use of non-renewable resources and substituting renewables in their place.

A transition to an economy based solely on renewable feedstocks will be extremely difficult (Rees and Wackernagel 1995, Clark 1997) and is unlikely to be brought about by minor improvements in eco-efficiency alone. Considering that the very development and explosive growth of western industrialized economies during the last 200 years was actually fueled by the discovery, exploitation, and use of non-renewables such as iron, coal, petroleum, trace-metals, minerals, etc. (Youngquist 1997), it becomes obvious what a daunting task it will be to reverse this deep-rooted and inherently unsustainable path. Nothing but a complete redesign of the very foundations on which industrial societies are based is required to achieve inherent sustainability. In fact, almost all current agricultural, industrial, and economic activities would have to be drastically and fundamentally changed. This will be a major challenge, not only technically but also politically, socially, and culturally. Clearly, it is naïve to believe that tinkering with eco-efficiencies alone will bring about a transition to a sustainable society.

But even if the goal of eliminating the use of all non-renewables could be achieved, this still would not per se guarantee sustainability. This is because a significant amount of energy is required to run the industrial processes within the circular flow economy and the generation of any energy is associated with negative environmental impacts. Considering the limited amount of remaining fossil fuels (Romm and Curtis 1996, Campbell and Laherrere 1998) and the extreme long-term hazards associated with nuclear energy generation, it is clear that in the future all energy must come from renewable sources, i.e., it must be directly or indirectly derived from solar energy. However, as will be shown next, it is impossible to generate renewable energy without causing negative environmental impacts, which, if large enough, would pose a threat to industrial and cultural sustainability.

Large-scale renewable energy generation is likely to have severe environmental impacts

It has been commonly assumed that renewable energy generation is more environmentally friendly than the use of nonrenewable energy sources such as fossil fuels or nuclear power (Hayes 1977, Lovins 1977, Brower 1992, Boyle 1996). While this assumption may be correct, it must be realized that the capture and conversion of solar energy will have significant negative environmental impacts, especially if they are employed on such a large scale as to supply nearly 100% of the U.S. energy demand (Abbasi et al. 1995, Trainer 1995a).

Before discussing some of the potential negative impacts of different solar energy technologies, it is useful to review the implications of the second law of thermodynamics in order to show that environmental impacts of renewable energy generation are inherently unavoidable. This is because the flux of solar energy (or neg-entropy) onto Earth is used to create highly ordered (i.e., low entropy) so-called "dissipative structures" in the environment (Nicolis and Prigogine 1977, Atkins 1984, Ayres 1998a). Evidence of such structures can be seen in the complexity of organisms, ecosystems, biodiversity, and carbon and nitrogen cycles, all of which are maintained by the constant in-flow of solar energy (Ayres and Martinas 1995).

If the flow of solar energy were to stop, as it ultimately will in a few billion years, all these complex structures would decay and reach a final equilibrium state where entropy is maximized. Similarly, if humans divert a fraction of solar energy away from the environment to create ordered structures for their own purposes (i.e., houses, appliances, transportation infrastructure, communication systems, etc.), less energy is available to maintain highly ordered dissipative structures in nature. The disturbance of these structures translates into the various environmental impacts that are associated with renewable energy generation.

As shown in Fig. 3, the total amount of solar energy (ΔE_s) that is received on Earth can be viewed as the sum of energy diverted for human purposes (ΔE_h) and energy that remains available to maintain "order" in the environment (ΔE_e):

$$\Delta E_s = \Delta E_e + \Delta E_h \tag{2}$$

According to the second law of thermodynamics, energy (ΔE) is used to decrease the entropy (ΔS) (increase the order) of a system at temperature T [K] according to (Faber et al. 1995):

$$\Delta E = -T\Delta S \tag{3}$$

Combining Eqs. (2) and (3) yields:

$$\Delta E_s = -T\Delta S_e - T\Delta S_h \tag{4}$$

where ΔS_e and ΔS_h are the change in entropy (order) in the environment and human-dominated sub-system, respectively. Combining Eqs. (2) and (4), it follows that a change of entropy in the environment is related to a change of entropy in the human-dominated subsystem according to:

$$\Delta S_e = \frac{-\Delta E_s}{T} - \Delta S_h \tag{5}$$

Since the total flow of solar energy (ΔE_s) is constant, it follows that, for each unit of "order" (neg-entropy) created by the diversion of solar energy in the human-dominated subsystem, at least one unit of "disorder" (entropy) is caused in the environment as evidenced by a wide range of dierent environmental disturbances[4].

Thus, *the second law of thermodynamics dictates that it is impossible to avoid environmental impacts (disorder) when diverting solar energy for human purposes.*This prediction, based on the second law of thermodynamics, should be no surprise considering the numerous roles solar-based energy flows play in the environment (Holdren et al. 1980, Haefele 1981, Clarke 1994). For example, direct solar energy radiation is responsible for the heating of land masses and oceans, the evaporation of water, and therefore the functioning of the entire climatic system. Wind transports heat, water, dust, pollen, and seeds. Rivers are responsible for oxygenation, transport of nutrients and organisms, erosion, and sedimentation. The capture of solar energy via photosynthesis results in biomass that provides the primary energy source for all living matter and therefore plays a vital role in the maintenance of ecosystems (Clarke 1994).

According to energy expert John Holdren, the potential environmental problems with solar energy generation can be summarized as follows: "Many of the potentially harnessable natural energy flows and stocks themselves play crucial roles in shaping environmental conditions: sunlight, wind, ocean heat, and the hydrologic cycle are the central ingredients of climate; and biomass is not merely a potential fuel for civilization but the actual fuel of the entire biosphere. Clearly, *large enough interventions in these natural energy flows and stocks can have immediate and adverse effects on environmental services essential to human well-being*" (Holdren et al. 1980, 248).

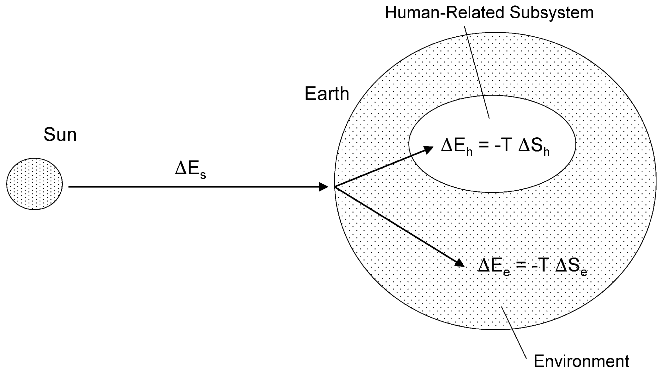

Fig. 3. Diversion of solar energy to human-related subsystems results in entropy increase in the environment

Table 2 summarizes the potential environmental impacts for the six main renewable energy sources, i.e., direct solar, solar thermal, photovoltaics, wind power, hydroelectric, and biomass energy. These solar technologies differ substantially in their requirement for land area. While direct solar heating of buildings would not require any additional area, the creation of new lakes for hydroelectric energy generation and the establishment of biomass plantations would require large areas of land. For example, Pimentel et al. (1994) have estimated that ca. 20% of the U.S. land area would have to be dedicated to solar energy generation to produce 37 quads (10.7×10^{12} kWh), which is only ca. 40% of current total U.S. energy demand. From this it can be seen that the availability of land might become a limiting factor in solar energy generation if close to 100% of the future U.S. energy demand has to be supplied by renewables.

It should also be noted that a large amount of renewable and non-renewable resources will be required to manufacture the solar energy capture technologies. For example, how much steel and concrete will be required to build tens of millions of passive solar energy collectors and photovoltaic solar panels or several million windmills? (Bezdek et al. 1982, Bezdek 1993). Even using the best precautions, some pollution will occur during the manufacture and use of solar energy technologies. A particular concern may be the handling of the hundreds of millions of lead batteries used in energy storage and the leaching of fertilizers and pesticides that are applied in biomass plantations.

Finally, some of the most difficult problems to assess are potential eco-system impacts. These may range from simple interventions such as the removal of shade trees to bird and insect kills in windmills. Since photosynthetically fixed energy (i.e., biomass) supports the great diversity of species inhabiting ecosystems (Vitousek et al. 1986, Wright 1990), it follows that removal of this energy source will result in the endangerment and extinction of species. For example, it has been determined that a reduction of

[4] For a discussion on how potential entropy increase is related to negative environmental impacts, see also Ayres and Martinas (1995), and Huesemann (2001).

Table 2. Examples of potential environmental impacts for renewable energy sources (Holdren et al. 1980,Clarke 1994, Pimentel et al. 1994)

	Land required[a]	Use of renewable materials	Use of non-renew. materials	Pollution during manufact.	Pollution during use	Ecosystem effects	Other impacts
Direct solar	NA[b]	NA	Metals, glass	Particulates, air pollution	Coolant leaks	Removal of shade trees	Visual glare
Solar thermal	1,100	Water for cooling tower	Metal, glass, concrete	Particulates, air pollution	Coolant leaks	Fragile desert ecosystem	Burn and eye hazard (light beam)
Photovoltaics	2,700	NA	Heavy metals, glass	Toxic metal emissions	Disposal of toxic metals+lead batteries	Removal of shade trees+fragile ecosystem	Visual glare
Wind power	11,666	NA	Steel, concrete	Particulates, air pollution	Disposal of lead batteries	Bird and insect kill	Noise, aesthetics
Hydroelectric	75,000	Water	Concrete, steel	Particulates, air pollution	NA	Numerous negative effects	Microclimate, no free flow. rivers
Biomass energy	220,000	Water for irrigation	Fertilizers	NA	Fertilizers, pesticides, air pollution	Species ext., soil erosion, deforestat.	Dust, monoculture

[a] $ha/10^9\ kWh^{-1}\ year^{-1}$ (see Pimentel et al. 1994,Table 2)
[b] Not applicable

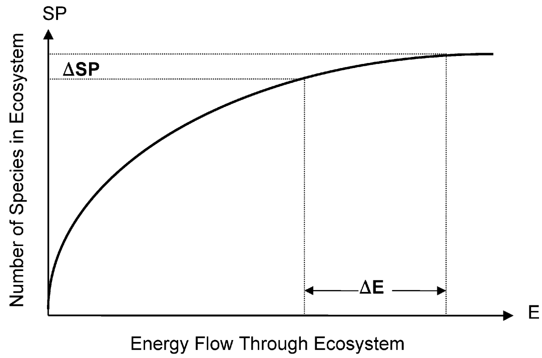

Fig. 4. Reduction in the energy flow through the ecosystem will result in a reduction of species in the respective ecosystem (adapted from Wright 1990)

energy flow through an ecosystem will result in a concomitant loss of species as shown in the species-energy curve in Fig. 4. Thus the greater the diversion of solar energy for human purposes (ΔE), the greater the loss of species diversity (ΔSP) (Wright 1990).

In summary, a wide range of negative environmental impacts are associated with the capture, generation, and storage of solar energy. These impacts are likely to be very significant if close to 100% of the U.S. energy demand has to be supplied by renewables, a condition that is becoming more probable as non-renewable fossil energy sources become much more expensive, especially after 2010, and as the search for sustainable energy solutions becomes more intense (Holdren 1990, Romm and Curtis 1996, Campbell and Laherrere 1998). Consequently, while it may be in principle possible to design future industrial processes that are for the most part environmentally benign by closing the materials cycle and using renewable feedstocks, it is inherently impossible to produce large amounts of solar energy without causing major environmental impacts.

The fact that large-scale renewable energy generation will create a wide range of negative environmental disturbances could pose a problem for the long-term sustainability of solar energy capture and use. As outlined in the first sustainability condition above, renewable resources including solar energy can only be "harvested" at rates that do not exceed the respective regeneration rates. If solar energy capture drastically disturbs important environmental functions, it is possible that these renewable energy production processes are not sustainable over the long run. For example, hydroelectric dams not only cause serious eco-system disruptions (e.g., salmon migration) but also interfere with the normal downstream transport of silt. As a result, reservoirs fill up with sediments, which means that most hydroelectric projects have only a limited lifetime and are therefore not sustainable (Reisner 1986, 491).

While it may in principle be possible to develop solar energy capture systems that are technically sustainable for long periods of time, it is important to recognize that there are actually many "sustainability states" that can be chosen among those that are technically feasible. What type of sustainability endpoint is aimed for critically depends on our values and what type of world we want to create and live in. According to Daly, we have to choose between either anthropocentric or biocentric values (Daly 1996, 52). For example, two alternative visions of the future could be imagined, both of which may be sustainable from a purely technical perspective. Following the current technocratic path, we could turn more than 50% of the U.S. land area into short-rotation tree monocultures that can be harvested for biomass energy at sustainable rates. Similarly, we could dot the landscape with millions of huge noisy windmills and unsightly power-poles and cover half of American Southwest land area with photovoltaic cells. We could also dam every conceivable river and creek and push many aquatic species over the brink to extinction. All this would be necessary to maintain the current standard of living for the current U.S. population at the cost of an impoverished environment that has few other species, no wilderness, and is monotonous and sterile. Alternatively, it could be envisioned that we simplify our lifestyle, drastically reduce population, and only minimally interfere with natural processes to meet our limited energy needs. As a result, we would live in a world that is rich in diversity and natural beauty. The choice is ours!

Using renewable energy as an example, it is therefore clear that sustainability involves more than just the technical issue of eco-efficiency. There are, in fact, different degrees of sustainability we can aim for and our choice depends on our values and vision of the future[5]. Improvements in eco-efficiency are unable to deal with these vital matters. This is not surprising since eco-efficiency addresses only the technical means of improving environmental performance but not the ultimate goal of actually defining sustainability.

Based on the above analyses it follows that it will be extremely difficult to avoid the many negative environmental impacts caused by industrial activities because it is impossible to completely close the materials cycle, and large-scale renewable energy generation is likely to cause numerous environmental problems. In case these arguments are not convincing to the multitude of technological optimists who believe that human ingenuity can solve any problems (Sagoff 1995, Ausubel 1996) and that it therefore should be in principle possible to design "clean" and "environmentally friendly" industrial economies, it may be constructive to review the second law of thermodynamics. As will be discussed next, it is inherently impossible from a thermodynamic viewpoint to design industrial technologies that have no negative environmental impacts.

According to the second law of thermodynamics, all industrial production technologies have inherently unavoidable environmental impacts

The second law of thermodynamics states that the total entropy (S) within a closed system undergoing change must always increase with time (Prigogine 1961, Balzhiser et al. 1972, Rifkin 1980, Atkins 1984, Prigogine 1989, Ayres 1998a). Since entropy can be related to the chaos or disorder of a system via the Boltzmann equation (Atkins 1984), this is equivalent to stating that disorder must increase in closed systems. However, it is possible to increase the order within a small subsystem at the expense of creating more disorder in the rest of the system.

Consider, for example, the overall system of planet earth (PE) which can conceptually be divided into two domains (see also Fig. 1), namely the human-based economy (ECON) and the natural environment (ENV). Since most current industrial and economic activities are driven by non-renewable energy sources (>90 — see Pimentel et al. 1994) and do not require solar energy, we can—as a first approximation—formulate the simplifying assumption that from an economic perspective planet Earth is a closed system that does not receive matter or energy from outer space[6]. Then, according to the second law of thermodynamics, the total entropy of the closed system planet Earth (ΔS_{PE}) must increase with time as follows:

$$\Delta S_{\mathrm{PE}} = \Delta S_{\mathrm{ECON}} + \Delta S_{\mathrm{ENV}} > 0 \tag{6}$$

where ΔS_{ECON} and ΔS_{ENV} are the changes in entropy of the human economy and natural environment, respectively. Rearranging Eq. (6) yields:

$$\Delta S_{\mathrm{ENV}} > -\Delta S_{\mathrm{ECON}} \tag{7}$$

This Eq. (7) can be interpreted as follows: For each unit of "order" or neg-entropy ($-\Delta S_{\mathrm{ECON}}$) that is created in the human-based economy, more than one unit of "disorder" or entropy (ΔS_{ENV}) is created in the surrounding environment.

As was mentioned earlier, the human-generated "order" is generally related to the many physical artifacts and activities that are considered signs of civilization such as the endless array of consumer goods and services. In practice, a wide range of mining, manufacturing, transportation, and communication technologies are employed to create this highly ordered human environment. The second law of thermodynamics states that this ordered human environment cannot be created and maintained without causing more disorder elsewhere (Aryes and Nair 1984)[7].

This concomitant disorder created in the surrounding environment manifests itself in a wide range of health and environmental impacts. Since entropy is a measure of chaos or disorder, a number of investigators have in fact proposed entropy increase in the environment as an al-

[5] The fact that there is not just one fixed sustainability state but probably many different ones is also reflected in the analysis by Davidson (2000) who questions that there is a fixed environmental limit to economic growth. Instead, it is more reasonable to assume that environmental destruction occurs along a continuum and that, to use Davidson's tapestry metaphor, the beauty and functioning of the tapestry (i.e., biological systems) are gradually diminished as individual threads (i.e., species, beautiful places, and life-support services) are removed as a result of increasing economic growth.

[6] The fact that almost all present-day economic activities could continue unabated at night is evidence that they are almost completely uncoupled from the inflow of solar energy. Nevertheless, the conclusions reached in Eq. (7) also hold for open systems see Eq. (5).

[7] According to Rifkin: "Each technology always creates a temporary island of order at the expense of greater disorder in the surroundings." (Rifkin 1980, 123).

ternative measure for pollution. For example, Kuemmel (1989) has used entropy as a pollution indicator in macroeconomic modeling and Faber et al. (1995) have suggested the formulation of a pollution function in which entropy increase, due to dispersal and reaction of specific contaminants, is used as an aggregated measure of pollution. The use of entropy as a substitute indicator for environmental disturbance has also been recommended by Ayres who notes: "As waste materials approach local equilibrium with the environment, the potential for future entropy generation is a measure of their potential for driving uncontrolled chemical or physical processes in environmental systems. Eco-toxicity is nothing more or less than environmental disturbance. Thus, potential entropy can be regarded as a measure of the a priori probability of eco-toxicity[8]" (Ayres and Martinas 1995).

Using the above analyses, Eq. (7) can then also be interpreted as follows: For each unit of economic activity in the techno-sphere, more than one unit of environmental disruption is created in the bio-sphere. This fact was recognized several decades ago by N. Georgescu-Roegen, an economist who was the first to include entropy considerations in economic theory (Georgescu-Roegen 1971, 1977), who stated: "no one has realized that we cannot produce 'better and bigger' refrigerators, automobiles, or jet planes without producing also 'better and bigger' waste." (Georgescu-Roegen 1980, p. 55).

If one defines "eco-efficiency" as the number of units of environmental disruption per unit economic activity (GDP)[9], it is clear that the second law of thermodynamics sets a lower limit beyond which it is impossible to improve eco-efficiency further (Ayres and Miller 1980, Ruth and Bullard 1993). In short, the environmental impact of current industrial and economic activities may be substantially reduced through R&D in industrial ecology and its allied disciplines (Sagoff 1995, Ausubel 1996), but it can never be reduced to zero (Cleveland and Ruth 1999, Ehrlich et al. 1999). As will be discussed next, the latter point is of extreme importance if one considers the role that various societal factors play in contributing to the overall magnitude of environmental problems.

Improvements in eco-efficiency alone will not reduce the total environmental impacts if growth in consumption and population continues unrestrained

The total environmental impact of human economic activities is not solely caused by polluting technologies (T) but is also dependent on societal factors such as the size of the "consumer" population (P) and the per capita affluence (A). According to the commonly used "master equation", the cumulative environmental impact (I) can be estimated as the product of technological (T) and societal factors (P and A) as follows (Ehrlich and Holdren 1971, Graedel and Allenby 1995)[10]:

$$\begin{aligned}\text{Environmental Impact} &= PAT \\ &= \text{Population} \times \text{GDP/Person} \\ &\quad \times \text{Environmental Impact/Unit GDP} \\ &= \text{GDP} \times \text{Eco} - \text{Efficiency} \qquad (8)\end{aligned}$$

The term "Environmental Impact/Unit GDP" is often referred to as the "technology factor", reflecting the idea that technological improvements in eco-efficiency can be counted on as the main strategy in reducing the environmental impact of current economic activities (Allenby and Richards 1994, Ayres and Simonis 1994, Ausubel 1996, Ayres and Ayres 1996, DeSimone and Popoff 1997, Graedel and Allenby 1995, Allenby 1999). However, as has been pointed out above, the extent to which technology can improve the environmental performance of industrial economies is bounded by the second law of thermodynamics, i.e., the technology factor (T) can never become zero.

Recent estimates on the potential degrees to which eco-efficiencies can be improved have varied widely (Reijnders 1998). However, most researchers agree that an increase in eco-efficiency by a factor of two (i.e., a reduction of the T -factor by 50%) should be achievable in a relatively short time frame. For example, Von Weizsacker et al. (1997) provide numerous examples where the use of raw materials (i.e., the materials intensity) can be cut in half while maintaining economic growth. Similarly, various studies have shown that it should be possible to improve the energy efficiency of the overall economy (i.e., the energy intensity) by a factor of two (Williams 1987, Carlsmith et al. 1990). However, any further improvements in eco-efficiency would require substantial investments in research and development, and goals to achieve a "dematerialization" of the economy by a factor 10 reflect, in the words of Dutch industrial ecologist Reijnders, "a remarkable technological optimism" (Reijnders 1998, 13).

Assuming then that a two-fold improvement in eco-efficiency—or equivalently a 50% reduction in the T -factor—can be achieved within the next 20 to 30 years[11], it is possible to predict the change in the total environmental impact using Eq. (8). Figure 5 shows the relative magnitudes of eco-efficiency (T), the size of the economy (GDP), and total environmental impact (I) as a function of time assuming an annual GDP growth rate of 2.5%, a target

[8] It should be noted that the correlation between entropy increase and environmental damage is currently a hypothesis that requires verification using field and laboratory data. For a more in-depth discussion of this topic, the reader should refer to Cleveland and Ruth (1997), Connelly and Koshland (1997), Glasby (1988), Huesemann (2001), O'Connor (1994), and Ruth (1993, 1995, 1996).

[9] For comparison, energy intensity is defined as energy use per unit of GDP (Graedel and Allenby 1995, p. 19).

[10] As a first order approximation, it is assumed here that P, A, and T are independent variables that exhibit no significant interactions among them. However, as has been pointed out by Holdren (1991) and has been discussed in detail by Gaffin (1998) and O'Neill et al. (2001), these three variables are likely to influence each other, often in unexpected and complicated ways. Nevertheless, in order to obtain an approximate estimate of the total environmental impact (I) in terms of the separate contributions of P, A, and T, most investigators for simplicity assume that P, A, and T are independent of each other.

[11] For comparison, it took ca. 25 years (1959–1984) to reduce the energy intensity (energy use per unit GDP) of the U.S. economy by 50% (Graedel and Allenby 1995, p. 19).

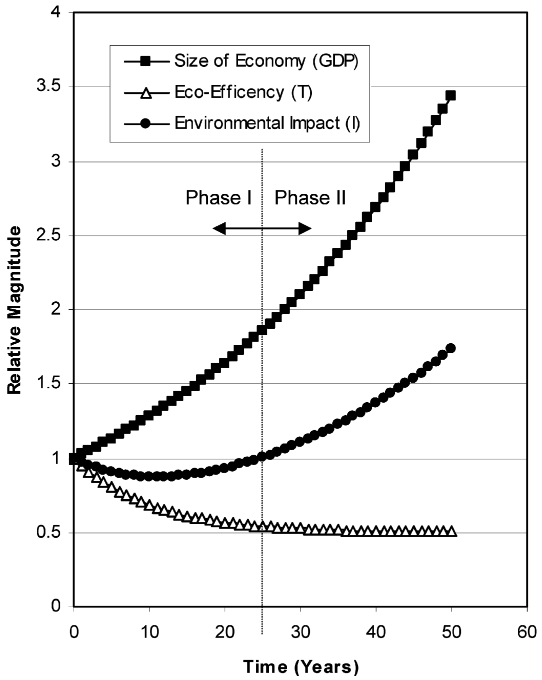

Fig. 5. Predicted changes in total environmental impact (I) according to Eq. (8) assuming a GDP growth rate of 2.5% per year and a maximum improvement in eco-efficiency (T) by a factor of two within the next 25 years

recommended by the President's Council on Sustainable Development (PCSD 1996).

As can be seen in Fig. 5, the total environmental impact decreases initially as improvements in eco-efficiencies occur faster than the simultaneous growth of the economy. However, after about 11 years there are no further reductions in the environmental impact as economic growth starts to outpace technological improvements in eco-efficiency. In fact, the total environmental impact starts to increase slowly and after 25 years has the same magnitude as it was initially. Unless eco-efficiency is improved again drastically at this point, the total environmental impact will continue to increase as long as the size of the economy is growing at a steady rate.

Based on the conceptual analysis shown in Fig. 5, it is possible to divide the eco-efficiency improvement process into two phases. During phase I, economic growth and enhanced environmental protection can go hand in hand, while during phase II continued economic growth in the absence of further eco-efficiency improvements will result in a progressive deterioration in environmental quality. Consequently, the commonly proclaimed statement by politicians and corporate leaders that it is possible to have both economic growth and environmental protection is at best a half-truth. It is only true for the short-term (i.e., phase I), when eco-efficiency improvements are occurring faster than increases in the size of the economy. However, this optimistic viewpoint is clearly incorrect in the long run (i.e., phase II), when continued economic growth will sooner or later outpace any improvements in eco-efficiency, since these will either become cost-prohibitive due to the law of diminishing returns characteristic of technological innovations or because of ultimate thermodynamic constraints.

The assertion that improved eco-efficiencies will not necessarily lead to decreased total environmental impact was proven correct by Ehrlich et al. (1999), who found that the total materials use, a proxy for total environmental impact, increased by up to 30% from 1975 to 1995 in the four countries studied (U.S.A., Germany, Netherlands, Japan) despite the fact that the materials use intensity (i.e., materials used per GDP) decreased approximately 30% during the same time period. Any hard-won improvements in materials use efficiency were clearly outpaced by simultaneous increases in the per capita consumption (A) and the size of the population (P), particularly in the United States. Similarly, in a study of dematerialization indicators, Cleveland and Ruth (1999) caution against the naïve belief that "technical change, substitution and a shift to the information age inexorably lead to decreased materials intensity and reduced environmental impact." They also warn that, despite improvements in the efficiency of use of individual materials, overall aggregate economic growth could increase total material consumption.

It is therefore clear that improvements in eco-efficiency alone can never guarantee the long-term reduction in environmental impacts or a transition to a sustainable society. A cursory analysis of Eq. (8) shows that eco-efficiency improvements could have a positive effect if the size of the economy (GDP) were to remain constant. However, historical evidence indicates that technological innovation has never been used to stabilize the size of the economy; in fact, technology's main role has always been exactly the opposite, namely the enhancement of industrial productivity, consumption, and economic growth (Samuelson and Nordhaus 1989, Schnaiberg and Gould 1994, Braun 1995, Nelson 1996). For example, labor-saving machinery and automation have been introduced to increase the efficiency of industrial production and thereby overcome the limitations that slow and expensive manual labor pose to economic expansion. Similarly, eco-efficiency improvements attempt to reduce the constraints that environmental pollution makes on industrial productivity growth. For instance, a plant's production cannot continue or expand if surrounding communities find the resulting air and water pollution unacceptable. Any improvements in air pollution control or waste water treatment will assure that the plant's production can resume or even expand. In summary, improvements in technological efficiency, including eco-efficiency, are always used to further the goal of industrial and economic expansion.

It is therefore ironic that eco-efficiency improvements are developed to ameliorate the various negative environmental impacts associated with economic growth while at the same time they actually promote further industrial and economic expansion. Since industrial ecology and pollution prevention strategies are addressing only the symptoms (i.e., pollution, etc.) of economic growth while ignoring the root-causes of unsustainability (i.e., economic growth), it can be concluded that most eco-efficiency enhancements are nothing more than short-term techno-fixes that delay the appearance of symptoms until they reappear in even more serious form at a later time. For example, better gas mileage for automobiles will reduce not only the amount of air pollution but also the fuel costs per mile driven. However, these fuel efficiency improvements will not lead to less overall automobile-caused air pollution if due to the resulting lower transportation costs people drive longer distances (A) and if the population of car drivers (P) continues to increase, as it has been doing steadily ever since the invention of this ubiquitous technological artifact (Schnaiberg and Gould 1994, Graedel and Allenby 1998). Thus, while fuel efficiencies are improved with the intention of reducing overall air pollution and greenhouse gas emissions, the long-term effects are in many ways worse than was initially anticipated: more cars, more traffic, more congestion, more development of the transportation infrastructure, more urban sprawl, and more use of material resources such as iron and concrete for highway construction, not less air pollution.

The fact that improvements in resource use efficiencies often result in an increased rather than a decreased aggregate consumption of the very same resource that was supposed to be conserved has been observed in many different spheres of the economy and is termed the rebound effect or Jevon's paradox (Rees and Wackernagel 1995, Mayumi et al. 1998, Cleveland and Ruth 1999). The reason for this unexpected finding is that efficiency gains look to consumers a lot like price reductions, which in turn increase the demand for energy and material resources directly through price elasticity effects or indirectly through the release of additional purchasing power that is redirected to other energy- and resources-using goods and services (Cleveland and Ruth 1999). This explains why energy efficiency gains since the Industrial Revolution have always gone hand in hand with increasing energy usage (Greenhalgh 1990). Similarly, the rebound effect is probably at least partially responsible for the fact that, despite improvements in the materials use per GDP, total materials use for countries such as the U.S.A., Germany, the Netherlands, and Japan has not decreased due to concomitant increases in per capita consumption (A) and population size (P) (Ehrlich et al. 1999).

It should therefore be clear that sustainability can only be achieved in the long run if the root causes of unsustainable behavior are successfully addressed. These are primarily our society's obsession with economic growth, which in turn is driven by an excessive desire for affluence (A) and a lack of limits on population growth (P). But the modifications of greed and procreation are obviously ethical and not technological issues. They require a commitment by people to change their deep-seated values and modify their destructive behavior. Eco-efficiency improvements cannot help to bring about this necessary change in values and behavior. At best, enhancements in eco-efficiency can buy some time for social and ethical action to address the underlying causes (Allenby 1999). Unfortunately no public discussion about the problems related to economic growth is taking place, probably because political and corporate leaders continuously bombard us with the half-truth that both economic growth and environmental protection are possible. Thus, technological optimism in eco-efficiency is in fact used to inhibit the much needed public discourse about the underlying causes of unsustainability. Consequently, current efforts at improving industrial eco-efficiency without addressing overconsumption and overpopulation are nothing more than, "putting off a socially and economically disruptive day of reckoning." (Stunkel and Sarsar 1994, 82).

The single-minded focus on technological eco-efficiency improvements may to a certain extent be justifiable and excusable if indeed various negative environmental consequences can be delayed by a few years. In reality, however, these harmful effects are not only delayed but often grow in complexity and severity as society continues down the inherently unsustainable path of economic expansion. In fact, the longer society moves in the wrong direction, the fewer options it will have in the future to respond to these extremely complex problems. Consider, for example, how difficult it will be to reverse our current dependence on the automobile. While the situation is certainly already bad, it will surely not be improved by a technology-induced expansion of automobile usage that in turn will most likely result in continuing changes in our settlement patterns. Unfortunately, as soon as new developments in housing and transportation systems are completed in response to greater automobile use, it is virtually impossible to change this rigid infrastructure. If society were forced for environmental or economic reasons to curtail automobile use in the future, it would have very few workable options to respond to this problem. Therefore, without restraints on economic growth, all technological improvements, including those in eco-efficiency, will only accelerate the speed with which we reach the unpleasant situation where we have almost completely lost our freedom to choose satisfying solutions for addressing the challenge of long-term sustainability.

Conclusions

It is clear from the above analysis that a transition to a sustainable society poses a number of serious technological challenges. First, considering that the very foundations of western industrial societies are based on the exploitation of non-renewable minerals and fuels, it will be extremely difficult to switch to an industrial and economic system based solely on renewable resources. Clearly, the continuing use of non-renewables is inherently unsustainable because of finite material supplies and the fact that 100% recycling is impossible. Second, given the limited supply of non-renewable fuels (fossil and nuclear), long-term sustainability can only be guaranteed if all energy is derived directly or indirectly from the sun. However, if the current U.S. energy demand would have to be supplied solely from solar sources, a wide range of serious and unavoidable negative environmental impacts are likely to result. Third, even the best of human ingenuity and the greatest technological optimism are bounded by the second law of thermodynamics, which dictates that all industrial and economic activities have unavoidable negative environmental consequences. Fourth and finally, improvements in eco-efficiency alone will not guarantee a reduction in the total environmental impact if economic growth is allowed to continue. Unless growth in both population and consumption is restrained, these technological improvements only delay the onset of negative consequences that, as a result, will have increased in severity, thereby reducing our freedom to choose satisfying solutions.

It is therefore clear that, in direct contradiction to the proclamations by many politicians and business people, eco-efficiency improvements alone can never assure the transition to sustainability. This point has also been repeatedly been made by many leading industrial ecologists. For example, Allenby (1999, p. 57) states: "... the evident limits to technological fixes are instructive: Consumers and society as a whole must not be left with the impression that simply relying on technology will avoid the need for difficult and complex political decisions. Better technology can buy time, but it cannot by itself buy sustainability." Similarly, Ayres (1998b, p. 366A) is also convinced that: "even if manufacturers produced as eco-efficiently as possible and eliminated all production wastes, the global system would be inherently unsustainable." In a recent article on the future of industrial ecology, Graedel (2000, p. 28A) is similarly questioning "whether these (technological) steps will achieve or even approach the desired aim of sustainability, which will require much more than a modest perturbation of today's technological society." Duchin and Lange (1994) used Leontief's world input-output model and also found that even the most strict efficiency standards proposed by the Brundtland report would not result in sustainability. Finally, steady-state economist Daly (1994, p. 96) recognized the limits of technological approaches long ago when he wrote: "... but unless the underlying growth paradigm and its supporting values are altered, all the technical prowess and manipulative cleverness in the world will not solve our problems and, in fact, will make them worse."

The principle reason why technological solutions by themselves are inherently insufficient in bringing about a transition to sustainability is related to a profound confusion between means and ends: It is currently believed that a change in technological means (i.e., eco-efficiency) will bring about a change in the end (i.e., sustainability). However, this is impossible since the endpoint of sustainability has never been defined. In fact, as was indicated above, the present goal is clearly still economic growth, and improvements in eco-efficiency actually promote this growth. Thus, as long as the goal is inherently unsustainable, no improvement in technological efficiency will ever bring about the opposite. As Daly (1980, p. 353) rightly mentioned earlier: "... if our ends are perversely ordered, then it is better that we should be inefficient in allocating means to their service." Thus, as long as there a commitment to inherently unsustainable goals such as economic expansion and growth, it may actually be better not to improve eco-efficiency in order to slow down the speed at which we travel in the wrong direction.

It is clear from the above discussion that eco-efficiency improvements are only useful if the endpoint is sustainability rather than economic growth. The first step in the right direction would be a transition to a steady-state economy where the throughput of matter-energy (i.e., the product of A and P, see Eq. 8) is held at "sustainable" levels (Daly 1980, Daly 1996). At present, nobody knows exactly what magnitude of matter-energy throughput is sustainable; the important point is that it must have an upper limit. As was pointed out earlier, the size of this upper limit is not only determined by technical and scientific considerations but is also strongly affected by ethical and social factors. For example, the size of the maximum sustainable matter-energy throughput depends on what type of world we would like to live in and whether we strive for an anthropocentric or biocentric optimum (Daly 1996, 52). Clearly, a society with strong biocentric values would choose a much smaller maximum matter-energy throughput than a society with a deep-seated anthropocentric bias.

In conclusion, improvements in eco-efficiency will only be effective if there is a commitment by society to limit the total throughput of matter-energy at sustainable levels. This most certainly would mean an end to the current addiction to economic growth and a transition to a steady-state economy. To achieve this it will be necessary to severely restrict and reverse population growth (Ehrlich and Ehrlich 1991) and to simplify our lifestyle by reducing our preoccupation with excessive consumption (Durning 1992, Trainer 1995b). It is clear that these required changes will pose serious ethical, social, and political challenges to the status quo. The very first step towards sustainability would therefore be a public discussion of these complicated and controversial value-laden issues. Unfortunately, this much needed public discourse on the personal, social, economic, and political changes necessary to achieve a sustainable society is not taking place, most likely because many are led to believe that technological solutions alone will be sufficient to guarantee sustainability. Nothing could be further from the truth.

Disclaimer

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

References

Abbasi SA, Abbasi N, Nipaney PC, Ramasamy EV (1995) Environmental impact of non-conventional energy sources. J Sci Ind Res 54:285–293

Allenby BR (1999) Industrial ecology: policy framework and implementation. Prentice-Hall, Englewood Cliffs, N.J.

Allenby BR, Richards DJ (1994) The greening of industrial ecosystems. National Academy of Engineering, National Academy Press, Washington, D.C.

Atkins PW (1984) The second law. Scientific American Books, WH Freeman, New York

Ausubel J (1996) Can technology spare the Earth? Am Sci 84:166–178

Ayres RU (1994) Industrial metabolism: theory and policy. In: Allenby BR, Richards DJ (eds), The greening of industrial ecosystems. National Academy Press, Washington, D.C., pp 23–37

Ayres RU (1996) Statistical measures of unsustainability. Ecol Econ 16:239–255

Aryes RU (1998a) Eco-thermodynamics: economics and the second law. Ecol Econ 26:189–209

Ayres RU (1998b) Toward a zero-emission economy. Environ Sci Technol August 1 Issue: 366A–367A

Ayres R (1999) The second law, the fourth law, recycling and limits to growth. Ecol Econ 29:473–483

Ayres RU, Ayres LW (1996) Industrial ecology: towards closing the materials cycle. Edward Elgar, Brookfield, Vt.

Ayres R, Martinas K (1995) Waste potential entropy: the ultimate ecotoxic? Econ Appl 48:95–120

Ayres R, Miller SM (1980) The role of technological change. J Environ Econ Manage 7:353–371

Ayres RU, Nair I (1984) Thermodynamics and economics. Phys Today November:62–71

Ayres RU, Simonis UE (1994) Industrial metabolism: restructuring for sustainable development. United Nations University Press, New York

Azar C, Holmberg J, Lindgren K (1996) Socio-ecological indicators for sustainability. Ecol Econ 18:89–112

Balzhiser RE, Samuels MR, Elisassen JD (1972) Chemical engineering thermodynamics. The study of energy, entropy, and equilibrium. Prentice-Hall, Englewood Cliffs, N.J.

Bezdek RH (1993) The environmental, health, and safety implications of solar energy in central station power production. Energy 18:681–685

Bezdek RH, Wending R, Bennington GE, Chew HR (1982) National goals for solar energy: economic and social implications. Nat Resour J 22:337–360

Bianciardi CE, Tiezzi E, Ulgiati S (1993) Complete recycling of matter in the frameworks of physics, biology, and ecological economics. Ecol Econ 8:1–5

Boyle G (1996) Renewable energy: power for a sustainable future. Oxford University Press, Oxford, UK

Braun E (1995) Futile progress: technology's empty promise. Earthscan, London

Brower M (1992) Cool energy: renewable solutions to environmental problems. MIT Press, Cambridge, Mass.

Campbell CJ, Laherrere JH (1998) The end of cheap oil. Sci Am March:78–83

Carlsmith RS et al. (1990) Energy efficiency: how far can we go? U.S. Department of Energy, Oak Ridge National Laboratory Report ORNL/TM-11441

Clark CW (1997) Renewable resources and economic growth. Ecol Econ 22:275–276

Clarke A (1994) Comparing the impacts of renewables. Int J Ambient Energy 5:59–72

Cleveland CJ, 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. Ecol Econ 22:203–223

Cleveland CJ, Ruth M (1999) Indicators of dematerialization and the materials intensity of use. J Ind Ecol 2:15–50

Connelly L, Koshland CP (1997) Two aspects of consumption: using an exergy-based measure of degradation to advance the theory and implementation of industrial ecology. Resour Conserv Recycling 19:199–217

Constanza R, Daly HE (1992) National capital and sustainable development. Conserv Biol 6:37–46

Constanza R, Patten BC (1995) Defining and predicting sustainability. Ecol Econ 15:193–196

Daly HE (1980) Economics, ecology, ethics: assays toward a steady-state economy. WH Freeman, New York

Daly H (1994) Steady-state economics. In: Merchant C (ed) Ecology key concepts in critical theory. Humanities Press, Atlantic Highlands, N.J.

Daly HE (1996) Beyond growth: the economics of sustainable development. Beacon Press, Boston, Mass.

Davidson C (2000) Economic growth and the environment: alternatives to the limits paradigm. BioScience 50:433–440

DeSimone LD, Popoff F (1997) Eco-efficiency: the business link to sustainable development. MIT Press, Cambridge, Mass.

Duales System Deutschland AG. For additional information on the German "Green Dot" program, visit http://www.gruener-punkt.de/e/index.htm

Duchin F, Lange G-M (1994) The future of the environment: ecological economics and technological change. Oxford University Press, New York

Durning AT (1992) How much is enough? The consumer society and the future of the Earth. WW Norton, New York

Ehrlich PR (1989) The limits to substitution: meta-resource depletion and a new economic-ecological paradigm. Ecol Econ 1:9–16

Ehrlich PR, Ehrlich AH. (1991) The population explosion. Touchstone Books

Ehrlich PR, Holdren J (1971) Impact of population growth. Science 171:1212–1217

Ehrlich PR, Wolff G, Daily GC, Hughes JB, Daily S, Dalton M, Goulder L (1999) Knowledge and the environment. Ecol Econ 30:267–284

Faber M, Niemes H, Stephan G (1995) Entropy, environment, and resources. Springer, Berlin Heidelberg New York

Gaffin SR (1998) World population projections for greenhouse gas emission scenarios. Mitigation Adaptation Strategies Global Change 3:133–170

Georgescu-Roegen N (1971) The entropy law and the economic process. Harvard University Press, Cambridge, Mass.

Georgescu-Roegen N (1977) The steady-state and ecological salvation: a thermodynamic analysis. BioScience 27:266–270

Georgescu-Roegen N (1980) The entropy law and the economic problem. In: Daly HE (ed) Economics, ecology, ethics: assays toward a steady-state economy. WH Freeman, New York

Glasby GP (1988) Entropy, pollution and environmental degradation. Ambio 17:330–335

Graedel TE (2000). The evolution of industrial ecology. Environ Sci Technol 34:28A–31A

Graedel TE, Allenby BR (1995) Industrial ecology. Prentice Hall, Englewood Cliffs, N.J.

Graedel TE, Allenby BR (1998) Industrial ecology and the automobile. Prentice Hall, Upper Saddle River, N.J.

Greenhalgh G (1990) Energy conservation policies. Energy Policy, April:293–299

Gutes MC (1996) The concept of weak sustainability. Ecol Econ 17:147–156

Haefele W (1981) Energy in a finite world: a global systems analysis. Chapter 10: Energy and climate. Ballinger, Cambridge, Mass.

Hayes D (1977) Rays of hope: the transition to a post-petroleum world. WW Norton, New York

Holdren JP (1990) Energy in transition. Sci Am September: 157–163

Holdren JP (1991) Population and the energy problem. Popul Environ 12:231–255

Holdren JP, Morris G, Mintzer I (1980) Environmental aspects of renewable energy sources. Annu Rev Energy 5:241–291

Houghton JT (1997) Global warming: the complete briefing. 2nd edn. Cambridge University Press, Cambridge, UK

Huesemann MH (2001) Can pollution problems be effectively solved by environmental science and technology? An analysis of critical limitations. Ecol Econ 37:271–287

Hueting R, Reijnders L (1998) Sustainability is an objective concept. Ecol Econ 27:139–147

Kuemmel R (1989) Energy as a factor of production and entropy as a pollution indicator in macroeconomic modeling. Ecol Econ 1:161–180

Kuik O, Verbruggen H (1991) In: Search of indicators of sustainable development. Kluwer, Boston, Mass.

Lovins AB (1977) Soft energy paths: toward a durable peace. Ballinger, Cambridge, Mass.

Mayumi K, Giampietro M, Gowdy JM (1998) Georgescu-Roegen/Daly versus Solow/Stiglitz revisited. Ecol Econ 27:115–117

Nelson RR (1996) The sources of economic growth. Harvard University Press, Cambridge, Mass.

Nicolis G, Prigogine I (1977) Self-organization in non-equilibrium systems: from dissipative structures to order through fluctuations. Wiley, New York

O'Connor M (1994) Entropy, liberty and catastrophe: the physics and metaphysics of waste disposal. In: Burley P, Foster J (eds) Eco-

nomics and thermodynamics: new perspectives on economic analysis. Kluwer, Boston, Mass., pp 119–182
O'Neill BC, MacKellar FL, Lutz W (2001) Population and climate change. Cambridge University Press, Cambridge, UK
Organization for Economic Cooperation and Development (OECD) (1998) Eco-efficiency, OECD, Paris
O'Riordan T (1993) The politics of sustainability. In: Turner RK (ed) Sustainable environmental economics and management. Belhaven, New York, pp 37–69
Pearce DW, Atkinson GD (1993) Capital theory and the measurement of sustainable development: an indicator of weak sustainability. Ecol Econ 8:103–108
Pimentel D, Rodrigues G, Wang T, Abrams R, Goldberg K, Staecker H, Ma E, Brueckner L, Trovato L, Chow C, Govindarajulu U, Boerke S (1994) Renewable energy: economic and environmental issues. BioScience 44:536–547
President's Council on Sustainable Development (PCSD) (1996) Sustainable America: a new consensus for the prosperity, opportunity and a healthy environment for the future. http://www.whitehouse.gov/PCSD/Publications/
Prigonine I (1961) Thermodynamics of irreversible processes. Wiley, New York
Prigogine I (1989) What is entropy? Naturwissenschaften 76:1–8
Rees WE, Wackernagel M (1995) Our ecological footprint: reducing human impact on the Earth. New Society Publishers, Gabriola Island, BC
Reid D (1995) Sustainable development: an introductory guide. Earthscan, London
Reijnders L (1998) The factor X debate: setting targets for eco-efficiency. J Ind Ecol 2:13–21
Reisner M (1986) Cadillac desert: the American West and its disappearing water. Viking Penguin, New York
Renning K, Wiggering H (1997) Steps towards indicators of sustainable development: linking economic and ecological concepts. Ecol Econ 20:25–36
Rifkin J (1980) Entropy a new world view. Viking, New York
Romm JJ, Curtis CB (1996) Mideast oil forever? Atlantic Mon 277:57
Ruth M (1993) Integrating economics, ecology and thermodynamics. Kluwer, Dortrecht, The Netherlands
Ruth M (1995) Information, order and knowledge in economic and ecological systems: implications for material and energy use. Ecol Econ 13:99–114
Ruth M (1996) Evolutionary economics at the crossroads of biology and physics. J Social Evolutionary Syst 19:125–144
Ruth M, Bullard CW (1993) Information, production, and utility. Energy Policy 21:1059–1066
Sagoff M (1995) Carrying capacity and ecological economics. BioScience 45:610–620
Samuelson PA, Nordhaus WD (1989) Economics, 13th edn. McGraw-Hill, New York
Schmidheiny S (1992) Changing course: a global business perspective on development and environment. MIT Press, Cambridge, Mass.
Schnaiberg A, Gould KA (1994) Environment and society: the enduring conflict. St. Martins Press, New York
Skinner BJ (1987) Supplies of geochemically scarce metals. In: McLaren DJ, Skinner BJ (eds) Resources and world development. Wiley, New York, pp 305–325
Stunkel KR, Sarsar S (1994) Ideological values and technology in political life. University Press of America, Lanham, Md.
Tainter JA (1988) The collapse of complex societies. Cambridge University Press, Cambridge, UK
Trainer FE (1995a) Can renewable energy sources sustain affluent society? Energy Policy 23:1009–1026
Trainer T (1995b) The conserver society: alternatives for sustainability. Zed Books, London
Vitousek PM, Ehrlich PR, Ehrlich AH, Matson PA (1986) Human appropriations of the products of photosynthesis. BioScience 36:368–373
Von Weizsacker EU, Lovins A, Lovins H (1997) The factor four. Earthscan, London
Welford R (1997) Hijacking environmentalism: corporate responses to sustainable development. Earthscan, London
Williams RH (1987) Exploring the global potential for more efficient use of energy. In: McLaren DJ, Skinner BJ (eds) Resources and World development. Wiley, New York, pp. 211–244
World Commission on Environment and Development (1987) Our common future. Oxford University Press, Oxford, UK
Wright DH (1990) Human impacts on energy flow through natural ecosystems, and implications for species endangerment. Ambio 19:189–194
Youngquist W (1997) GeoDestinies: the inevitable control of Earth resources over nations and individuals. National Book Company, Portland, Oreg.