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ANALYSIS

Can pollution problems be effectively solved by environmental science and technology? An analysis of critical limitations☆

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Abstract

It is currently believed that science and technology can provide effective solutions to most, if not all, environmental problems facing western industrial societies. The validity of this optimistic assumption is highly questionable for at least three reasons: First, current mechanistic, reductionist science is inherently incapable of providing the complete and accurate information which is required to successfully address environmental problems. Second, both the conservation of mass principle and the second law of thermodynamics dictate that most remediation technologies — while successful in solving specific pollution problems — cause unavoidable negative environmental impacts elsewhere or in the future. Third, it is intrinsically impossible to design industrial processes that have no negative environmental impacts. This follows not only from the entropy law but also from the fact that any generation of energy is impossible without negative environmental consequences. It can therefore be concluded that science and technology have only very limited potential in solving current and future environmental problems. Consequently, it will be necessary to address the root cause of environmental deterioration, namely, the prevailing materialistic values that are the main driving force for both overpopulation and overconsumption. The long-term protection of the environment is, therefore, not primarily a technical problem but rather a social and moral problem that can only be solved by drastically reducing the strong influence of materialistic values.

Keywords: Environmental science and technology; Pollutant remediation; Entropy; Mechanistic reductionism; Industrial ecology; Paradigm shift; Post-normal science

1. Introduction

'The deterioration of the environment produced by technology is a technological problem for which technology has found, is finding, and will continue to find solutions' (Bereano, 1976, p. 10).

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Although this statement was made more than 30 years ago, little has changed since then with respect to our belief that technology is both the primary cause of and solution for environmental problems. In fact, during the last three decades, tremendous efforts in science and technology have been made to better understand the nature of environmental deterioration and to develop technologies to remediate the effects of past pollution. It is safe to say that hundreds of millions of dollars have been devoted to improve the quality of the environment and that much more will be spent in the future.

Despite these intense efforts expended in 'saving the environment', it is questionable whether current scientific and technological approaches can be sufficiently effective in solving our numerous environmental crises. This is because the current practice of environmental science and technology is based on the following three assumptions, the validity of which are highly problematic:

1. Science can provide us with enough detailed knowledge about nature to solve and prevent environmental problems.
2. Remediation technologies can successfully remove pollution without causing other unforeseen negative environmental impacts elsewhere.
3. It is possible to prevent pollution in the future and develop 'clean' industrial processes that have no environmental impacts.

It is surprising that most environmental scientists and engineers have never questioned the validity of these three assumptions, particularly in view of the fact that the success of their work, namely, the protection of the environment, critically depends on the accuracy of these premises. In addition, no rigorous examination of the soundness of these hypotheses can be found in the literature. It is therefore the objective of this paper to critically examine these three assumptions and to provide a better understanding of the intrinsic limitations of technological approaches to solving environmental problems.

2. Mechanistic reductionist science is inherently limited in providing complete and accurate information about environmental problems

For more than 300 years, the western cultures of Europe and North America have placed heavy emphasis on the experimental sciences for gaining a deeper understanding of nature and the universe. It is important to recognize that the philosophers of the Enlightenment did not promote the sciences because it would expand knowledge for its own sake, but because it had the potential for improving a culturally defined quality of life. According to Eugene Schwartz, 'the principal aim of knowledge for Francis Bacon, as for most of the other precursors of the school of scientific progress, was the utilitarian goal of improving man's condition by lessening his suffering and increasing his happiness. Casting aside the viewpoint of the Greek philosophers that knowledge affords its own intellectual satisfaction, Bacon defined the true goal of the sciences to be 'the endowment of human life with new inventions and riches'. He called on man 'to establish and extend the power and dominion of the human race itself over the universe' (Schwartz, 1971, p. 23–24).

It is clear, then, that modern science was from the very beginning never value-free and objective (Huesemann, 2000a). By contrast, the pursuit of science was and still is strongly motivated by societal needs to improve living conditions and, according to the utilitarian dogma, to maximize the happiness of the greatest number of people (DesJardins, 1993, p. 29). It is not surprising that scientific knowledge was almost immediately converted, with the help of engineers, into useful technologies which promised to fulfill the wishes of society. The strong utilitarian emphasis explains the heavy focus on mechanistic, reductionist research whose logic is based on two tacit assumptions, namely, that nature functions like a machine and that nature's complexity can be understood by investigating the properties of its isolated parts. According to Longino, 'mechanistic research is favored because it enables the manipulation of nature' (Longino, 1990, p. 94). Similarly, Sarewitz concludes that 'reductionst sci-

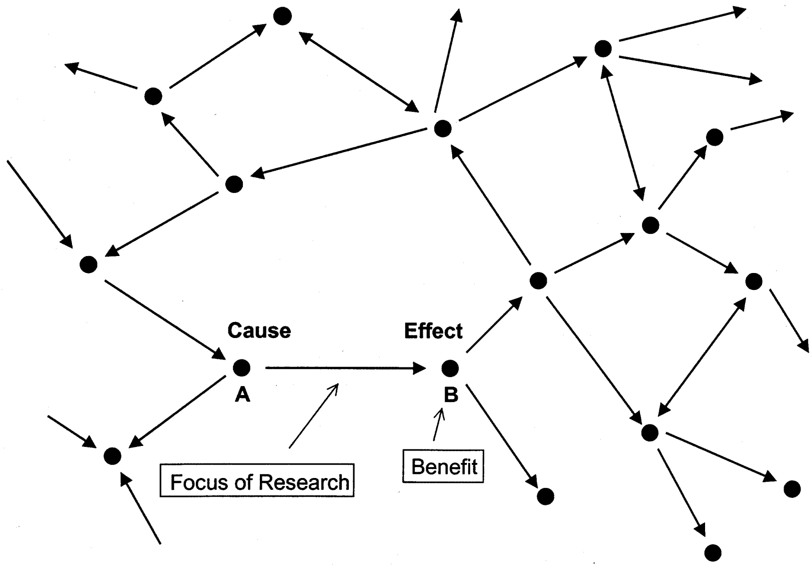

Fig. 1. Mechanistic, reductionist research focuses exclusively on cause and effect relationship A–B while ignoring all other effects and interactions.

entific research helped to forge the path to the post-industrial world by elucidating specific natural phenomena that could be isolated, manipulated, and applied to practical tasks' (Sarewitz, 1996, p. 105).

Fig. 1 shows conceptually how mechanistic, reductionist research is used to focus on isolated cause and effect relationships in order to exploit nature for some perceived benefit. In most cases, after the cause and effect relationships have been elucidated by scientific methods, efforts are taken to enhance desirable effects by manipulating causative factors. However, since the natural world more nearly resembles a large network of intricately connected cause and effect relationships[1], enhancement of one isolated effect is certain to have unexpected consequences elsewhere in the system or at a later time. These undesirable effects often manifest themselves as environmental pollution or various eco-system disturbances. Thus, it can be seen that western sciences have promoted the exploitation of nature and thereby have become a significant causative factor in the current environmental crisis.

Unfortunately, many environmental scientists are not aware of the inherent limitations of their research methodologies in solving environmental problems. This was clearly recognized by Sarewitz who wrote: 'Modern reductionist science was born explicitly of the moral obligation to know the polyphony of nature — and to conquer it. But even scientists who are passionately committed to understanding and reversing the ecologic crisis may strongly resist the notion that the character of science itself is in any way connected to the crisis' (Sarewitz, 1996, p. 112). Commoner is also convinced that 'the reductionist methodology, which is so characteristic of much modern research, is not an effective means of analyzing the vast natural systems that are threatened by degradation' (Commoner, 1971, p. 189). Similarly, in their research on post-normal science, Funtowicz and Ravetz point out that '... the methodology for coping successfully with these novel problems cannot be the same as the one that helped create them. Much of the success of traditional science lay in its power to abstract from uncertainty in knowledge and values... Now scientific expertise

[1] Remember also Commoner's First Law of Ecology: 'Everything Is Connected to Everything Else' (Commoner, 1971, pp. 33–39).

has led us into policy dilemmas which it is incapable of resolving by itself. We have not merely lost control and even predictability; now we face radical uncertainty and even ignorance, as well as ethical uncertainties lying at the heart of scientific policy issues' (Funtowicz and Ravetz, 1993, p. 741–742).

It is therefore questionable whether current scientific methods that are strongly biased towards the exploitation of nature can be used to provide sufficiently complete and accurate information to protect against the effects of this exploitation. In order to remediate the effects of past pollution or to protect against future environmental damage, it is necessary to understand all possible cause and effect relationships that might occur in nature as a result of human manipulations. Even if only one cause and effect relationship is overlooked during a scientific investigation, it may well prove to be an extremely critical one that could cause serious harm if ignored. A good example is the massive use of fossil fuels for energy and transportation needs. For many years, most researchers were single-mindedly focussed on reducing the impacts of various air-pollutants such as SO_2 or NO_x. Meanwhile, the potential effects of CO_2 were completely ignored until recently when it was found that increasing atmospheric CO_2 concentrations are a causative factor in global warming (Houghton, 1997). What if researchers were to have gained this insight 50 years from now when any remedial action would likely to be too late to be effective (assuming that it is not too late at this point in time). For that matter, what other critical cause and effect relationships are currently being overlooked?

Present scientific methodologies provide only very limited knowledge about the workings of nature as a whole, and environmental science elucidates only certain isolated aspects that were specifically chosen for investigation. It should therefore be clear that mechanistic, reductionist environmental research, by its very nature, can never elucidate all the interconnected relationships that exist in the natural world. For instance, it will never be possible to determine all the adverse effects synthetic chemicals may have in the environment. Scientific research has up to now focussed only on a few selected chemicals and their detectable effects on a very small subset of target species or organs. In theory, if one would like to know the total and complete impact of synthetic chemicals on the environment, it would be necessary to determine all possible adverse effects of all synthetic chemicals, pure and in mixture, on all species. In practice, this is impossible because: (a) the detection of adverse effects is limited by the state-of-the-art of current scientific knowledge and methodologies (e.g. the endocrine disruption potential of chlorinated synthetic chemicals could not have been predicted 50 years ago due to lack of biological assays for the measurement of endocrine disruption); (b) the testing of millions of different chemicals and chemical mixtures is cost-prohibitive; (c) there are millions of species, many of which have not been identified; and (d) the potential effects on future generations are impossible to measure or predict.

Considering the limited budgets for environmental research, it is obvious that only a few selected cause and effect relationships can ever be studied. But the elucidation of only a few selected issues considered important to humans clearly does not provide sufficient knowledge to protect all of nature. Consequently, the focus of current environmental science is too narrowly anthropocentric to truly ensure the long-term protection of human health and welfare. As a result, conservation biologist Ehrenfeld, who sees contemporary science and technology as an expression of an overly anthropocentric humanistic culture, is convinced that 'there is no true protection of Nature within the humanist system — the very idea is a contradiction of terms' (Ehrenfeld, 1981, p. 202). This concern was also expressed by policy analyst Sarewitz who stated:

> 'Because mainstream science is reductionist while the environment is an interconnected, complex system, much of modern science and technology may be intrinsically unsuited to successful confrontation of ecological crises … Ultimately, therefore, that reductionist science and its technological consequences can save us from ecological crises should be viewed with skepticism' (Sarewitz, 1996, pp. 107–113).

3. The conservation of mass principle inherently limits the effectiveness of physical remediation technologies

The conservation of mass principle is concisely stated in Barry Commoner's Second Law of Ecology: 'Everything Must Go Somewhere' (Commoner, 1971, p. 39). Thus, a pollutant, if not transformed naturally by either chemical or biological reactions, will remain indefinitely in the environment and its total mass will not change with time. Many physical treatment technologies attempt to reduce the risk posed by a pollutant using various strategies such as: (a) limiting the dispersal of the contaminant (e.g. landfilling); (b) reducing toxic effects by dilution (e.g. smokestacks); or (c) transferring contaminants from one medium to another (e.g. air-stripping of contaminated water).

Since the total mass of pollutant is not reduced by physical treatment technologies, their respective effectiveness in solving environmental problems is highly questionable. It is clear that physical treatment technologies transfer risks either from one place to another or from the present to the future. For example, landfilling limits the dispersal of contaminants only at the present time. Since it is unlikely that landfill integrity can be maintained indefinitely, contaminants can be expected to reenter the environment thereby causing negative effects for future generations.

The rationale of diluting pollutants or transferring contaminants from one medium to another has been justified by assuming that these treatment strategies make the pollutants less harmful. As was pointed out above, this assumption is very weak considering that mechanistic, reductionist science is inherently unable to elucidate all negative environmental consequences. For example, dilution will certainly reduce the risk of localized obvious acute toxicity, but is likely to increase the probability of more widespread subtle chronic effects that are currently unknown or difficult to monitor. Similarly, it is uncertain whether transfer of a pollutant from one medium to another will actually reduce the overall risks. More likely, this type of treatment strategy is chosen because the hazards of a pollutant in one medium are well known (i.e. chlorinated solvents in groundwater used for drinking) while very little data are available about the same compound in the medium to which it is transferred (i.e. chlorinated solvents dispersed in air).

In summary, *physical treatment technologies are unable to provide effective solutions to environmental pollution since they transfer risks either from one place to another or from the present to the future*. Physical treatment technologies are often considered effective only because spatially and temporally transferred risks are not known and because there is little general concern about what happens elsewhere or at a later time.

4. According to the second law of thermodynamics, all remediation technologies have unavoidable negative environmental consequences

The second law of thermodynamics states that the total entropy (S) within a closed system must always increase with time (Prigogine, 1961; Balzhiser et al., 1972; Rifkin, 1980; Atkins, 1984; Prigogine, 1989; Faber et al., 1995; Rebane, 1995; Ayres, 1998). 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. The second law of thermodynamics can be used to show why many remediation activities generate unavoidable negative environmental consequences.

Consider, for example, the common problem of cleaning up highly dispersed organic contaminants such as benzene or chlorinated solvents in groundwater (Bedient et al., 1994). As shown in Fig. 2A, the total entropy S_0^t of the closed system prior to the pollution event ($t = 0$) is the sum of the entropy of the subsystem S_0^s (consisting of the drum with the contaminant, the soil layer and the clean aquifer) and the entropy of the surrounding environment[2] S_0^e. As the chemical leaks from the

[2] For simplicity, it is assumed that the surrounding environment is a closed system. In reality, however, planet earth is an open system that receives solar energy from the outside universe. Nevertheless, the overall conclusions reached below (Eq. (3)) hold for both closed and open systems — see also Eq. (7).

drum and disperses through the soil layer and is dissolved in the groundwater (Fig. 2B), the entropy (disorder) of the subsystem increases to S_1^s. Since the environment (outside the box) is not affected, the entropy S_1^e remains unchanged from S_0^e. However, as predicted by the second law of thermodynamics, the total entropy ($S_1^t = S_1^s + S_1^e$) of the closed system increases as a result of the pollution event.

In a successful remediation effort such as 'pump and treat' (Fig. 2C), the dispersed pollutant is removed from the soil and aquifer, concentrated and placed in the second drum for either subsequent disposal or treatment. From a thermodynamic perspective, the cleanup effort consists of converting a highly entropic, disordered environment back to its original, low entropy condition (as in Fig. 2A). In short, during remediation, the entropy of the contaminated subsystem is reduced from S_1^s to S_2^s. The question now arises, how can entropy in the subsystem be reduced without violating the second law of thermodymamics?

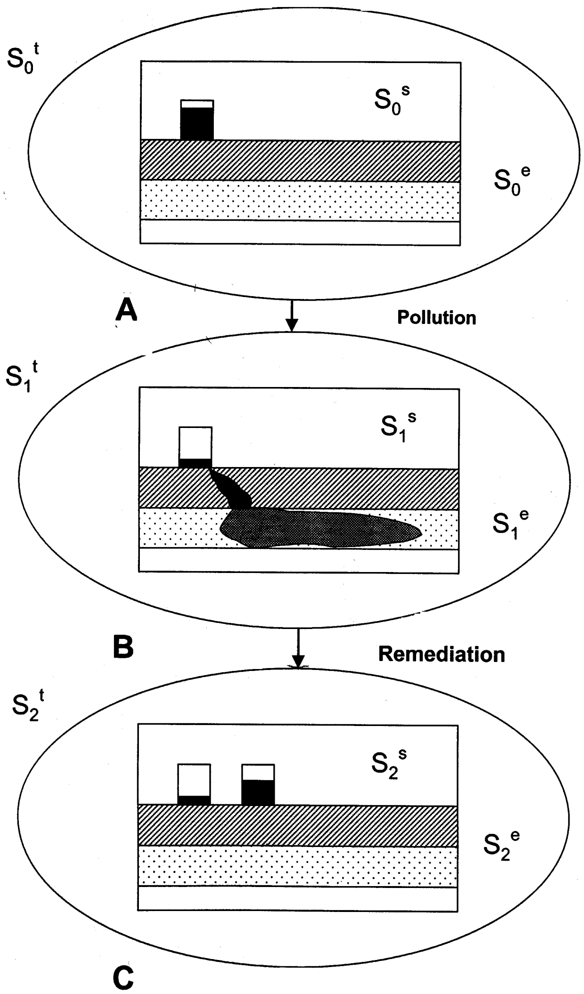

Fig. 2. Changes in entropy of the subsystem (S^s) and the environment (S^e) from initial clean state (A) to polluted (B) and final remediated (C) state. As elaborated in more detail in the text, the following relations hold: $S_2^t > S_1^t > S_0^t$; $S_1^s > S_0^s$; $S_2^s < S_1^s$; $S_2^e > S_1^e = S_0^e$.

According to the second law, the entropy of the total system must increase from S_1^t to S_2^t, i.e.

$$S_2^t > S_1^t, \tag{1}$$

Since $S_t = S_e + S_s$, it follows:

$$S_2^e + S_2^s > S_1^e + S_1^s. \tag{2}$$

Rearranging Eq. (2) and defining the change of entropy in the environment and the subsystem as $\Delta S^e = S_2^e - S_1^e$ and $\Delta S^s = S_2^s - S_1^s$, respectively, it follows:

$$\Delta S^e > -\Delta S^s. \tag{3}$$

Thus, remediation activities can create order in the subsystem ($-\Delta S^s$) *only at the expense of generating more disorder in the rest of the environment* (ΔS^e).

The main reason why disorder (entropy) is created in the environment is due to the fact that energy is needed to generate order inside the subsystem. According to established thermodynamic principles, energy generation is only possible by converting low entropy materials (coal, petroleum, natural gas, uranium) into high entropy wastes (carbon dioxide, sulfur dioxide, nitrous oxide, radioactive materials, waste heat, etc.). Since energy production takes place outside the subsystem, the net entropy increase occurs in the rest of the environment where it causes various undesirable effects.

The obvious next question is: How is entropy related to environmental pollution? Since entropy is a measure of chaos or disorder, it is not surprising that a number of investigators have proposed entropy increase in the environment as an alternative measure for pollution. For example, Kümmel

(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 rationale for using 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 nor less than environmental disturbance. Thus, potential entropy can be regarded as a measure of the a priori probability of eco-toxicity' (Ayres and Martinas, 1995, p. 116).

A chemical that is released accidentally can increase entropy in the environment by two primary mechanisms, namely, physical dispersion and unwanted chemical reaction. It is interesting to note how these two entropy-increasing mechanisms have a parallel with the common risk paradigm (Klaassen et al., 1986) which states that chemicals only pose a health or environmental risk if there is an exposure pathway (i.e. chemicals need to disperse to reach a sensitive receptor) and if the chemical is hazardous to the receptor (i.e. drives unwanted chemical reactions that are deleterious to the organism). Based on this assessment, it appears appropriate to use the potential for entropy increase as a substitute measure for environmental pollution. In fact, the entropy-pollution paradigm can be used to understand remediation efforts from a new perspective. Remediation technologies generally attempt to reverse or limit entropy increase in the affected environment either by controlling or reversing pollutant dispersion or by having the contaminants react to reach chemical equilibrium (the state where entropy is maximized) before they have a chance to disperse in the environment and reach sensitive receptors. Examples of both remediation strategies will now be discussed.

One of the most common environmental remediation approaches for controlling and reversing dispersion of dissolved groundwater contaminants is the 'pump and treat' technology (Bedient et al., 1994). Considering that there are more than 250 000 leaking underground storage tanks in the U.S. (Bedient et al., 1994) and that — as a result — many aquifers are polluted with either petroleum hydrocarbons or chlorinated solvents, many of which pose a health risk to water users, it is not surprising that environmental technologies have been designed to limit or reverse the dispersion of these dissolved groundwater contaminants. During 'pump and treat', contaminated groundwater is pumped from the aquifer, the contaminant is removed from the water, and the cleaned groundwater is reinjected. Since many groundwater contaminants sorb to the aquifer materials and are only slowly released into the aqueous phase, it often takes many years to remove the groundwater pollutants.

For demonstration purposes, let's assume that 1 000 000 gallons of groundwater are polluted with benzene at an average concentration of 0.5 ppm. Thus, a total of $\frac{1}{2}$ gallon of benzene needs to be removed from the aquifer. Assuming that a minimum of 5 years of 'pump and treat' is necessary to reach cleanup objectives and that the groundwater pump is operated by a diesel engine requiring five gallons of diesel per day, it follows that a total of 9125 gallons of diesel fuel are needed for the cleanup effort.

According to the second law of thermodynamics (see Eq. (3)), it follows that the increase of entropy in the environment due to diesel combustion is greater than the entropy reduction in the aquifer due to the removal of $\frac{1}{2}$ gallon of benzene. If entropy can be used as a measure for pollution, it follows that limited groundwater cleanup is carried out at the expense of greater atmospheric pollution consisting of highly dispersed contaminants such as SO_2, NO_x, particulates, and CO_2, the latter of which contributes to global warming (Houghton, 1997).

The common rationale for carrying out these types of remediation efforts is that the principle objective is the cleanup of groundwater. Considering the limited focus of environmental science, it is not surprising that any other side effects are seldom considered. Even if one would try to do so, mechanistic reductionist environmental science would be hopelessly ineffective in providing useful answers. For example, how would it ever be possible to determine all the risks associated with the widespread dispersal of the numerous air-pollutants including the greenhouse gas CO_2 whose effects on climate change, sea-level rise, and species extinction are extremely complicated? And how can these risks ever be objectively compared to all the health and environmental risks that result from $\frac{1}{2}$ gallon of carcinogenic benzene dissolved in 1 000 000 gallons of groundwater?

What happens in practice is that only the obvious problems are addressed, i.e. those situations where sufficient scientific evidence is available to indicate that environmental pollutants are present and might pose a risk to humans or whatever humans value. All other environmental problems, including those caused by remediation efforts, are ignored either because mechanistic environmental science has not yet elucidated the cause and effect relationships or because impacts occur elsewhere (preferably far away) or affect receptors that are not currently considered important. In short, whatever is scientifically known and sufficiently valued is addressed, whatever is unknown or not valued receives no attention. For example, benzene in groundwater is of concern because it is known to be carcinogenic. By contrast, the fact that pump and treat technology causes distant air-pollution effects (acid rain, smog, ozone, etc.) and future global warming is ignored because the impacts are not obvious and immediate. It can therefore be concluded that remediation technologies which attempt to reverse pollutant dispersion appear to be effective only when viewed from a very limited perspective. However, when one considers all side-effects, both spatially and temporally, it is extremely questionable whether these remediation technologies can truly improve the quality of the overall environment.

It should be noted that from a practical perspective most highly dispersed persistent contaminants are unlikely to ever be removed from the environment. Again, the second law of thermodynamics predicts that it requires tremendous amounts of energy to concentrate highly dispersed materials (Faber et al., 1995). This is why no serious attempts have been made to remediate persistent chlorinated pesticides such as DDT, now found in the fatty tissue of almost every organism in the world, or lead contamination along U.S. roads and freeways that is the result of earlier use of leaded gasoline, or the widespread metal and hydrocarbon contamination in many harbor sediments. In short, *as soon as contaminants have dispersed into the environment, remediation technologies are extremely ineffective in addressing the problem — in fact, overzealous attempts might well be counterproductive.*

This leads to the second type of remediation technologies that are designed to limit entropy increase in the environment by 'neutralizing' offending compounds before they disperse into the environment where they might drive harmful chemical reactions. A simple example is the neutralization of acid waste with alkali to create a mixture of neutral pH that is much less harmful than the original waste. There are many remediation technologies that use either chemical or biological reactions to render the waste stream much less reactive prior to release into the environment. From an entropy perspective, the waste reaches chemical equilibrium (i.e. maximum entropy) in the reaction chamber instead of the environment. Examples of chemical and biological treatment technologies are incineration, neutralization, and bioremediation.

While chemical and biological treatment technologies are certainly more effective than those remediation efforts that simply attempt to limit or reverse contaminant dispersal, it is important to realize that many of these technologies also have undesirable side-effects (Barton et al., 1996; Page et al., 1998). For example, incineration might generate flue gases that contain minute quantities of dioxins that are highly toxic. In addition, ashes containing toxic metals are generated and have to be dealt with (see section on physical treatment technologies). Even bioremediation, a low impact technology relying on native bacteria to metabolize pollutants, can cause the formation of intermediates that are more toxic than the original contaminant (e.g. carcinogenic vinyl chloride during chlorinated solvent bioremediation (Baker and Herson, 1994)). Also, the addition of certain process chemicals that are used to stimulate bioremediation may have a negative impact on the local soil or sediment ecology.

Consider finally the energy requirements and the resulting waste heat that is emitted into the environment as a result of pollution-control processes. According to Kümmel and Schüssler (1991), it is possible to calculate the 'heat equivalents of noxious substances' which is defined as the waste heat generated by pollution control technologies and which can be used as an aggregate pollution index in economic modeling. This approach shows that substance emissions can in principle be converted via pollution control processes into heat emissions, which are generally considered a more benign form of environmental pollution. However, the entropy-exporting waste heat emissions could become critical when the anthropogenic heat input into the biosphere, which is currently around 10^{13} W, reaches the maximum permissible 'heat barrier' of about 3×10^{14} W (Von Buttlar, 1975). For example, the wastewater treatment plant at the BASF chemical plant complex in Germany uses as much energy as a city of 50 000 inhabitants (Faber et al., 1995). Not only are large amounts of waste heat emitted into the environment as a result of this treatment but, as shown in more detail below, additional environmental deterioration is always associated with any form of energy generation. In summary, *even effective chemical and biological remediation technologies are likely to have negative environmental impacts*, *many of which may not be addressed because of the narrow focus of current environmental science and technology*.

5. It is impossible to design industrial processes that have no negative environmental impacts

Because most remediation technologies are not very effective in dealing with dispersed contaminants and since — based on the second law of thermodynamics — secondary negative consequences of cleanup operations are inherently unavoidable, it has been proposed that industrial processes be redesigned in such a way as to make them virtually emission-free so that environmental pollution is prevented in the first place. Consequently, during the last decade, environmental research began focusing on pollution prevention, and even a new academic discipline, industrial ecology, was born with the mission to design zero-emission industrial processes (Allenby and Richards, 1994; Ayres and Simonis, 1994; Graedel and Allenby, 1995; Ayres and Ayres, 1996; DeSimone and Popoff, 1997; Allenby, 1999).

As shown in Fig. 3, current economic activities are causing serious pollution in the environment for at least two major reasons. First, more than 90% (Pimentel et al., 1994) 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. The second reason for the highly polluting nature of the current U.S. industrial system is related to the fact that materials flow in a linear fashion through the economy (Fig. 3A). 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 impacts to ecosystems.

As was pointed out above, it is the 'mission' of industrial ecology to redesign current industrial processes in a way to make them more sustainable and compatible with the environment (Allenby and Richards, 1994; Ayres and Simonis, 1994; Graedel and Allenby, 1995; Ayres and Ayres, 1996; DeSimone and Popoff, 1997; Allenby, 1999). In order to avoid the numerous negative impacts associated with the dispersal of wastes into the environment, industrial ecologists have focused most of their attention on 'closing the materials cycle' (Graedel and Allenby, 1995; Ayres and Ayres, 1996; Allenby, 1999). As shown in Fig. 3B, it may be in theory possible to almost completely isolate the economy from the environment by recycling all wastes into materials that can be manufactured into consumer products. While 100% recycling is thermodynamically not feasible (Bianciardi et al., 1993), it may nevertheless be possible to greatly reduce the dissipation of wastes and the associated pollution effects. In addition, many industrial processes might also be

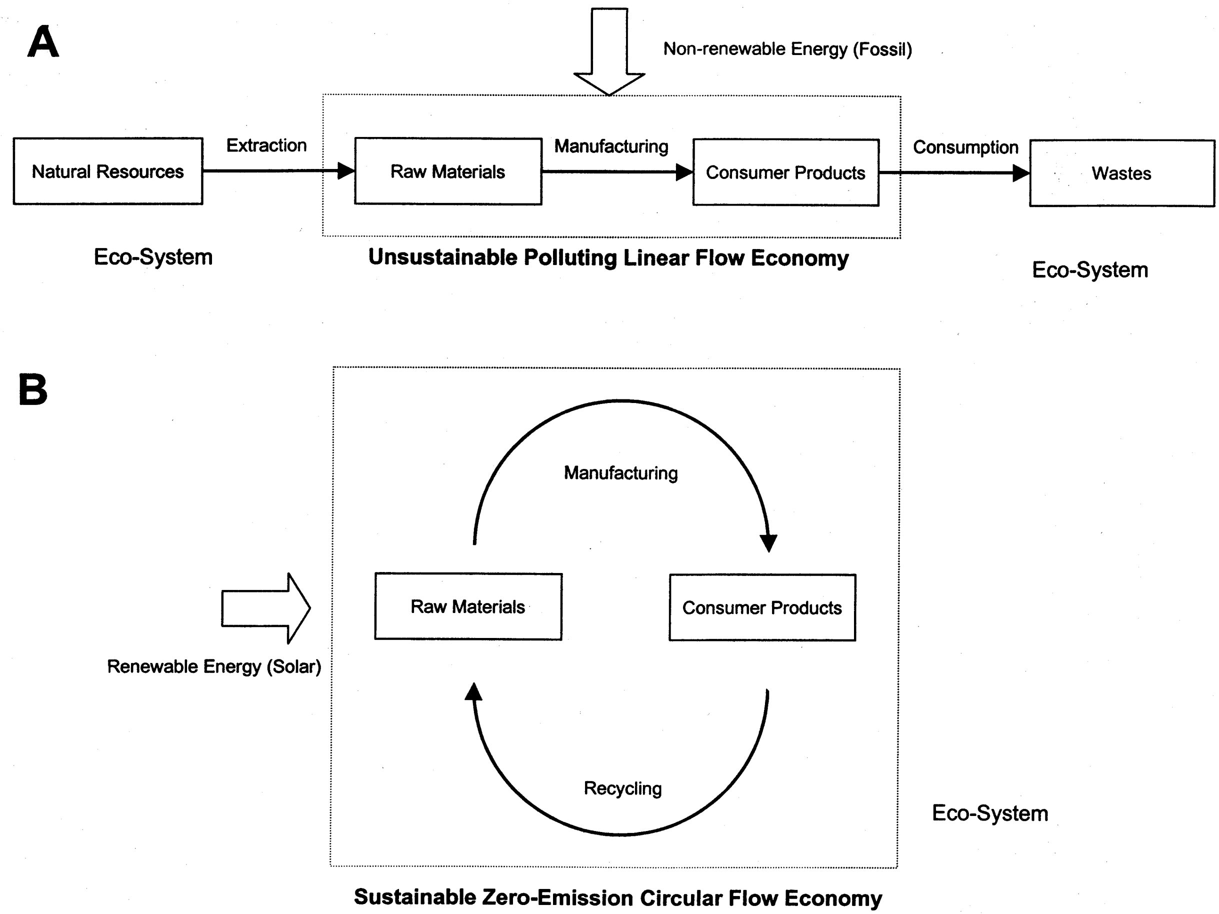

Fig. 3. Present unsustainable polluting linear flow economy (A) and future sustainable zero-emission circular flow economy (B).

redesigned to eliminate the presence of toxic byproducts or wastes so that material releases to the environment, if they were to occur by accident, are relatively harmless. In summary, by closing the materials cycle and eliminating the release of toxics, it may well be possible to design future industrial processes that are virtually emission-free and have a negligible impact on the environment.

However, a most important point that is commonly overlooked by most industrial ecologists and pollution prevention specialists is the fact that a significant amount of energy is required to run the zero-emission industrial processes within the circular flow economy, and that 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. Consequently, in an economy consisting of zero-emission industrial processes driven by renewable energy, the only remaining environmental impacts are those related to the conversion of solar energy. In other words, while it may be possible to design industrial processes that are virtually emission free, it is not possible to avoid the numerous negative environmental consequences related to solar energy production.

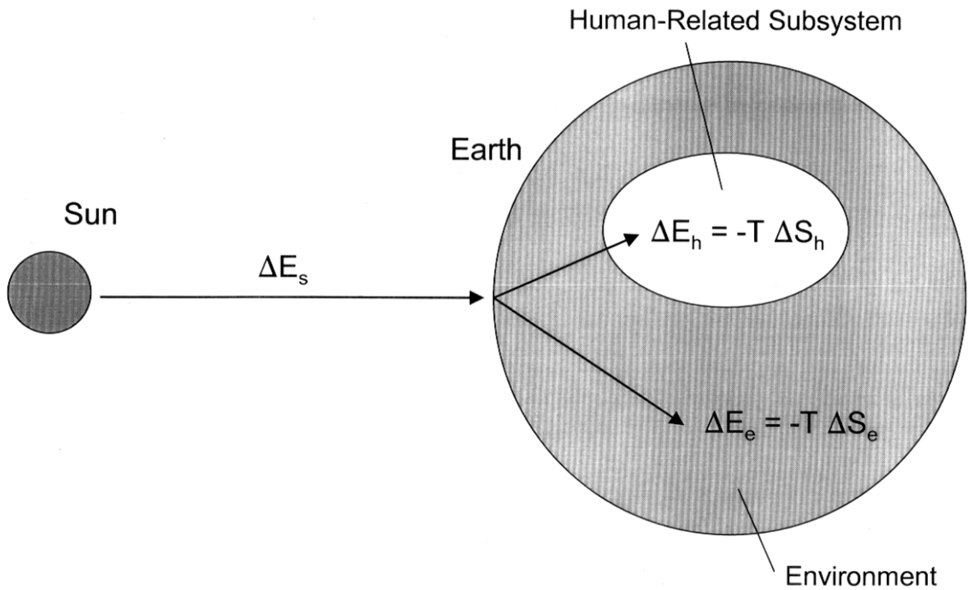

Fig. 4. Diversion of solar energy to human-related subsystems results in entropy increase in the environment.

It has been commonly assumed that renewable energy generation is more environmentally friendly than non-renewable energy sources such as fossil fuels or nuclear power (Brower, 1992; Boyle, 1996; Hayes, 1977; Lovins, 1977). 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.

Before discussing some of the potential negative impacts of different solar energy technologies, it is useful to review again the implications of the second law of thermodynamics in order to show that environmental impacts of renewable energy generation are inherently not avoidable. 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). 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 these 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. 4, 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):

$$\Delta E_s = \Delta E_e + \Delta E_h. \tag{4}$$

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)[3]:

$$\Delta E = -T \cdot \Delta S. \tag{5}$$

Combining both Eq. (4) and Eq. (5) yields:

$$\Delta E_{\mathrm{s}} = -T \cdot \Delta S_{\mathrm{e}} - T \cdot \Delta S_{\mathrm{h}}, \tag{6}$$

where ΔS_{e} and ΔS_{h} are the change in entropy (order) in the environment and human-dominated sub-system, respectively. Combining Eq. (4) and Eq. (6), it follows that a change of entropy in the environment is related to a change of entropy in the human-dominated subsystem according to:

$$\Delta S_{\mathrm{e}} = \frac{-\Delta E_{\mathrm{s}}}{T} - \Delta S_{\mathrm{h}}. \tag{7}$$

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 'disorder' (entropy) is caused in the environment as evidenced by a wide range of different environmental disturbances.

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; 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, nutrient and organisms transport, 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 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, p. 248).

A significant environmental impact is likely to be related to the fact that large areas of terrestrial ecosystems have to be converted to either biomass monocultures or flooded to create lakes for hydroelectric energy generation. For example, Pimentel et al. (1994) have estimated that ca. 20% of the U.S. land area would have to be dedicated for solar energy generation to produce 37 quads, 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 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 hundreds of million lead batteries used in energy storage and the leaching of fertilizers and pesticides that are applied in biomass plantations.

[3] This relationship reflects the ideal case of equilibrium thermodynamics when heat transgresses across system boundaries in a reversible manner. Clearly, the flow of solar energy onto earth is a non-equilibrium process in which 'additional' entropy is generated as result of irreversible phenomena (Prigogine, 1961; Kümmel, 1994). Since the mathematical treatment of irreversible processes would greatly complicate the current analysis, it is omitted here for the sake of simplicity. The overall conclusions reached from the interpretation of Eq. (7) are the same assuming either equilibrium or non-equilibrium conditions.

Finally, one 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 inhabitating ecosystems (Vitousek et al., 1986; Wright, 1990), it follows that removal of this energy source will result in the extinction of species. For example, it has been determined that a reduction of energy flow through an ecosystem will result in a concomitant loss of species as shown in the species-energy curve in Fig. 5. 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 in principle be possible to design future industrial processes that are virtually emission-free, it is inherently impossible to produce solar energy without causing significant environmental impacts. *Thus, all industrial processes — however, well designed to be emission-free — will have unavoidable negative environmental impacts related to energy generation.*[4]

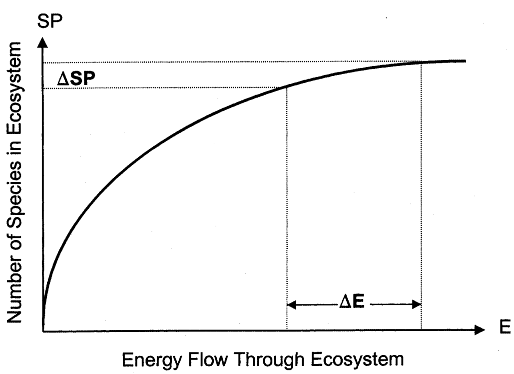

Fig. 5. Reduction in the energy flow through the ecosystem will result in a reduction of species in the respective ecosystem.

The critical reader might at this point express reservations about the above analyses since complex environmental phenomena are reduced to a single abstract entity such as entropy. Clearly, much more research is needed to experimentally define precisely the correlation between entropy generation and environmental pollution. However, a thermodynamic analysis of environmental technologies has a distinct advantage in that it deals with the entire system and not just one isolated aspect of it as traditional reductionist science. The second law of thermodynamics — like the law of gravity — applies everywhere and cannot be ignored when examining the effectiveness of environmental technologies.

6. Conclusions

Based on the above assessment, it is clear that modern science and technology have very limited potential to alleviate the numerous environmental problems facing western industrialized countries. This is due to the fact that: (a) reductionist, mechanistic science is inherently unable to provide complete and accurate information about current environmental problems; (b) the conservation of mass principle and the second law of thermodynamics both dictate that negative environmental consequences of remediation activities are in most cases intrinsically unavoidable; and (c) all industrial processes, even if designed to be emission-free, will have significant negative environmental impacts related to energy generation. *In many cases, environmental science and technology appear to be successful only because attention is focussed narrowly (in space and time) on specific objectives while wider, long-term impacts are ignored.*

Given these serious limitations, are there any roles that science and technology can play in

[4] For a more complete discussion of the limits of technological solutions to sustainable industrial development, see Huesemann (2000b).

guiding the development of environmental policies? Since the greatest strength of contemporary science is the detection of environmental disturbances and the elucidation of isolated cause and effect relationships, the main role of environmental science and technology should be to inform policymakers of the many negative impacts of past and current industrial activities so that actions can be taken to greatly modify or completely discontinue them as soon as possible. In addition, the development of ever more precise monitoring technologies will reduce the many uncertainties associated with the estimation of the extent and magnitude of environmental pollution.

As was pointed out earlier, most environmental problems are extremely complex and traditional reductionist scientific methods have been very limited in revealing the intricate web of far-reaching environmental interactions. In response to this limitation, environmental science has evolved in recent years to improve the understanding of the 'whole' instead of its isolated parts. This has been attempted by encouraging more interdisciplinary research, carrying out systems analyses, and by developing complex mathematical models that are run on supercomputers (Funtowicz and Ravetz, 1994a). Despite these new trends, it is still highly questionable whether these methods will ever be able to provide information that is sufficiently accurate to guide policy decisions. Consider, for example, the emergence of a new discipline called 'earth systems engineering' (Allenby, 1999, p. 3) whose mission is to find technological solutions to global problems such as the greenhouse effect. Despite eager attempts by scientists and engineers to develop various technological approaches to lower atmospheric CO_2 concentrations (DOE, 1999), it is almost guaranteed — given the high degree of scientific uncertainties — that these technological measures, if implemented, will cause serious, unexpected consequences elsewhere.

In their pioneering work on post-normal science, Funtowicz and Ravetz have proposed that the uncertainty of policy decisions related to the management of complex systems be decreased by extending the peer community to include not only scientists but also a variety of stakeholders such as representatives from industry, government, citizen groups and environmental organizations (Funtowicz and Ravetz, 1993, 1994a,b,c; Ravetz and Funtowicz, 1999). While this approach clearly has the advantage of reducing bias (Huesemann, 2000a) and enhancing democratic decision-making, it is still not clear how complex environmental problems can be solved given the high degree of scientific uncertainties and the unavoidable negative impacts of most, if not all, environmental technologies. However, the inclusion of many different stakeholders in policy decisions might finally lead to the recognition of the enormous importance of non-technical issues and to the discovery that changes in personal and social behavior may provide the only possible solutions to many complex environmental problems.

If technological solutions to environmental pollution are only of limited effectiveness, the question arises whether other alternative approaches can be found to deal with this serious and persistent problem. Again, the second law of thermodynamics can be used to provide answers by shedding light on the most fundamental causes of environmental disruption. According to the second law (see also Eqs. (3) and (7)), for each unit of 'order' that is created by human activities, more than one unit of disorder must be created in the surrounding environment.[5] 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. Conversely, the concomitant disorder created in the environment manifests itself in the wide range of health and environmental impacts. Consequently, environmental deterioration is directly related to the total quantity of human artifacts so that an increase in the quantity of artifacts will automati-

[5] This concept is also well captured by Rifkin (1980, p. 123) who wrote: 'Each technology always creates a temporary island of order at the expense of greater disorder in the surroundings.'

cally increase environmental disruption. The latter point is succinctly summarized by 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).

For simplicity sake, if we equate the total quantity of artifact production and related services within a nation to the gross domestic product (GDP), it is clear that environmental deterioration is directly related to the magnitude of the GDP according to the following equation (Graedel and Allenby, 1995):

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

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; Graedel and Allenby, 1995; Ayres and Ayres, 1996; DeSimone and Popoff, 1997; Allenby, 1999). However, as has been pointed out repeatedly in this paper, 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 can never become zero*.

Because of these thermodynamic limitations, it follows from Eq. (8) that the total environmental impact can only be effectively decreased by reducing either the size of the population (Ehrlich and Ehrlich, 1991) or the per capita consumption of goods and services (Georgescu-Roegen, 1980; Daly, 1996) (or both). If economic (GDP) growth is allowed to continue without limits, any potential reductions in environmental impact due to technological improvements in eco-efficiency will necessarily be short-lived. For example, let us begin with the rather optimistic assumption that it would take only 15 years[6] of intensive R&D to improve the overall eco-efficiency of the U.S. economy by 50%. This technological effort would cut the total environmental impact in half — but only if there is no growth in GDP during that 15-year period. Given the current addiction to economic growth, even a modest annual growth rate of 4% would double the GDP within 18 years. At that point, the total environmental impact would be the same as today and additional improvements in eco-efficiency would be again needed. At some point, eco-efficiency improvements are no longer possible because they become cost-prohibitive due to the law of diminishing returns characteristic of technological innovations or because of thermodynamic constraints (i.e. second law). In summary, while science and technology can in a limited way reduce the environmental impact of current economic activities, *long-term protection of the environment is only possible by reducing and limiting both the human population size and per-capita consumption* (*GDP/person*).

At this point it becomes clear that the root cause of the environmental crisis is the prevalence of materialistic values that are the driving force for the present — as Daly aptly called it — 'orgy of procreation and consumption' (Daly, 1980, p.123). Thus, long-term protection of the environment is not primarily a technological problem but a social and moral one. As was pointed out earlier, short-term techno-fixes are basically useless unless the limited time they buy is used to radically change our values and behavior. Unfortunately, the opposite has been the case: The public is led to believe that all problems are going to be solved by science and technology and that no change in values or behavior is necessary. Nothing could be farther from the truth.

[6] 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% — see Figure 2.3 in Graedel and Allenby (1995). During the same time period, the GNP grew more than 200% (Figure 9–2 in Samuelson and Nordhaus, 1989), indicating that total U.S. energy use did not decrease despite improvements in energy efficiency.

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