TECHNOLOGY AND THE ENVIRONMENT: AN OVERVIEW

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Technology and the Environment: An Overview

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ABSTRACT

The article starts with a brief history of the debate on the interactions between technology and the environment. A short overview of each article of this special issue is then presented. Three cross-cutting "metathemes" emerge from the articles. The first deals with the characteristics of uncertainty, ignorance, and dispersed knowledge that have historically characterized the generation and distribution of environmental and technological knowledge. The second addresses the issue of possible tensions that exist between the forces of technological inertia and the forces of environmentally induced technological change. Finally, some policy dilemmas between short- and long-term environmental preservation and technological change objectives are discussed.

Technology and Environment: a Brief History of Debate

In the early 1970s, a cluster of articles by Herbert Simon, Nathan Rosenberg, Vernon Ruttan, Chauncey Starr, and Richard Rudman [1–4] developed the same message (albeit through different lines of arguments): namely, that relevant and viable solutions to environmental problems call for more, and better mastery of, technology not less. To be precise, more "technology" would not necessarily mean more of today's technology or simple more technological "hardware," but would especially mean a deeper understanding of the mechanisms underlying technological change and the factors governing the diffusion of environmentally relevant technologies, as well as increased knowledge of the policy and institutional context that could promote or hamper required changes.

This message, which preceded or was in immediate response to the global modeling work of Forrester [5] and Meadows et al. [6], went largely unnoticed. The recurrent "anti-Malthusian" critique of models and world views of the "Limits to Growth" type by Simon and Kahn [7] and a group of Science Policy Research Unit (SPRU) scientists [8], also did not change the situation. The dominant "world view" considered technology inherently static; its extrapolation into the distant future inevitably led to resource depletion and environmental toxification. The newly emerging environmental movement also considered technology a major source of environmental degradation that would continue to generate unintended and unwanted side effects. At the same time, policy actions to address initial environmental issues most notably local air and water pollution, through legislation and regulation also relied on the dominant mode of thinking about technology

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and technological change. Environmental policies were largely directed toward forced diffusion of a host of incremental, "end-of-pipe" clean-up technologies. Technology remained a major "culprit" of environmental problems and was not seen as a possible answer to overcoming anticipated resource limits of either a physical or an environmental nature.

A certain change of perception and a rediscovery of the potential role of technology occurred late in the 1980s [9]. At that time, a more differentiated view of technology emerged. The "paradox of technological development" [10] describes technology as of a dual nature with respect to the environment: Technology has had an unprecedented impact on the environment, primarily through productivity increases that enabled substantial expansion of output (and consumption). Simultaneously, however, technological changes have also enhanced technological and economic capacities for remedies. Positive environmental influences of technology derive from three mechanisms: (1) at each moment, processes of technological substitution increase the efficiency of production modes and the usage of goods and services, providing new possibilities of overcoming limitations, e.g., of resource scarcity and depletion (the "age of substitutability" in the sense of Goeller and Weinberg [11]), or of overcoming limitations imposed by the absorptive capacity of the environment; (2) some technologies, such as satellite technologies, that do not enter any substitution process (they do not directly replace any old technology), can be qualified as "natural resource augmenting," e.g., enabling the discovery of new hydrocarbon or water reservoirs; and (3) technological change, or rather changes in a host of interrelated technologies, could (at least in principle) offer reductions in the resource, materials, and environmental intensiveness of industrial societies that are not only marginal, but rather are by orders of magnitude. This technological potential emerged from studies that charted long-term trends in materials and energy use ("dematerialization") that clearly illustrated orders-of-magnitude improvements since the beginning of the Industrial Revolution and identified similar orders-of-magnitude potentials for future improvements as well [12–15].

More than 20 years after the so-called "oil crises," there has also been a change in perception of the notion of absolute physical resource limits: the new view is that our definition of natural resources cannot be reduced to "simple" geological or mineral issues. Natural resource abundance is endogenous, technologically, economically, and socially constructed [16], and does not appear simply geologically predetermined.

Studies [14, 17] have also shown that technological change can be neither reduced to singular, discrete time events nor reduced to a limited number of "key" technologies. In particular, researchers that tried to determine why long-term economic growth is not a smooth continuous process quickly identified technology as something much more encompassing, ultimately consisting of whole clusters of interrelated technological, organizational, and institutional settings forming particular technoeconomic "paradigms" (in the sense of Freeman and Perez [17]. The environment was subsequently identified as being a possible decisive candidate in the reconfiguration of the entire technological landscape, or in the emergence of a "green" technoeconomic paradigm.

With such a notion, the problematique of technological change to solve environmental problems is becoming broader: transitions to cleaner technologies must not be limited to the energy and natural resource sectors. Because the problem at stake ultimately is a problem of changing social behaviors, consumption patterns, and lifestyles, technology must be considered holistically. Conversely, new technologies (such as information and communication technologies) could have a potentially large influence on, say, commuting and transportation, and thus possibly contribute to solutions. Nevertheless, it is fair to say that, in view of the multitude of environmental issues at stake and given that more than two-thirds of global population are still aspiring to the kind of resource- and environmental-intensive lifestyles of the affluent industrialized countries, a shift to an entire new technoeconomic "paradigm" seems required.

Whereas there has been progress in both conceptual ideas and empirical data charting long-term technology dynamics, progress in modeling has been far slower, if not disappointing. In essence the treatment of technology, technological change, and resources has not improved noticeably since the first generation of global models. Technology has largely remained exogenous, either falling like manna from heaven (in the form of "backstop" technologies saving the models from infeasibilities) or reduced to autonomous trend parameters that are hardly meaningful for policy. Resources, too, have remained largely exogenous, and fixed to a priori point estimates that reflect geological appraisals of reserves, but which most geologists, in turn, would refuse to consider as long-term resource potentials in view of persistent knowledge gaps and recurrent estimation blunders in the past. It is perhaps not surprising that the long-term future of both technology and the environment described by many global models and scenarios has not changed since the early 1970s. Forecasted "doomsdays" and short-term policy recommendations of such models and the "world view" they represent seem not to have changed much either [18].

Last but not least, during the 1994 and 1995 summer sessions of the "Technology and Environment" research network established at the International Institute for Applied Systems Analysis (IIASA) that led to this special issue, attention focused on a third role of technology: technology as a research tool—that is, as an instrument of (microscopic and macroscopic) observation, providing knowledge about the nature of environmental problems and about the effectiveness and efficiency of proposed or implemented solutions.[1]

Such a new view of technology, both as an instrument to reveal the nature and the extent of undesirable (environmental) side effects of technologies and as a possible solution to alleviate them through both incremental and radical change, suggests a new rationale for policy. It is no longer a matter of slowing down technological changes in the wake of uncertainty or anticipated environmental threats, by implementing regulatory standards, adding "end-of-pipe" technologies, and punishing innovators (see [19]). The problem is rather to accelerate and to increase the speed of diffusion of technologies that could become socially beneficial for diagnostic (e.g., environmental monitoring), explicative (environmental simulations), and "curative" measures; to increase the availability of options; to search for alternative solutions; and to create sufficient "escape velocity" from current entrenchments in undesirable technologies and practices.

Such a new policy rationale is, however, complex. The goal of environmentally sustainable development is a "moving target" and requires a wide range of complementary policies: on one hand, policies to support the generation of long-term technological alternatives and, on the other hand, policies to control environmental pollution in the short-term. A new organizational strategy seems necessary that enables both incremental (adaptationist) technological change (which can increase technological irreversibilities and "lock-in" phenomena) and the search for radical technological (and organizational) alternatives. The third potential role of technology—as an instrument to better understand our interactions with the environment and eventually to replace inadvertent "experiments" by simulation—is becoming critical. For instance, the ability to replace real experimentations by simulation in the field of nuclear weapons or to accelerate technological research by increasing the use of simulation to the detriment of prototype development (e.g., as

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[1] We are indebted to Marc Willinger (BETA, Louis Pasteur University, Strasbourg, France) for drawing our attention to this issue at the T&E Workshop, International Institute for Applied Analysis, Laxenburg, Austria, July 8-9, 1994.

done for the Boeing 777) indicates the possible emergence of a new mode of knowledge generation. (See Note Added in Proof at end of text.)

A Short Overview of the Articles in This Special Issue

This special issue on "Technology and Environment" includes eight articles. In this additional Introduction, we briefly present the main arguments developed in each article. The order of presentation follows the sequence of the articles as they appear in this issue and thus expresses a certain evolution of arguments and viewpoints. At the end of this Introduction, we present other interpretative "keys" for reading this special issue.

The model of "unanticipated discovery," elaborated by Thomas Schelling in the first article, can be viewed both as a revealing case study about a particular research pattern in the domain of nuclear weapons and as a metaphor of a more general process of disclosure of uncertainty and ignorance in the field of the interactions between technology and environment: the invention, diffusion, and use of technologies lead to a sequence of "discoveries by accident," which subsequently, and surprisingly, reveal properties, characteristics, and environmental impacts of technologies.

The article by Harvey Brooks complements the first one. It addresses the problem of attention management: it is not enough to generate knowledge about environmental impacts of technologies. That knowledge must be distributed to the right experts and policy-makers, that is to say persons with the capacity to take or to resist actions. (Schelling also discusses an attention management problem in his sketch of the development of energy studies and the greenhouse issue.) Such an "attention management" problem represents a clear departure from simplistic conceptions that "more information is better" and requires new modes for the integration of information from a much wider range of sources and networks of expertise than is available today.

Christopher Freeman, the author of the third article, closes this first sequence of articles by discussing the problematique of technology and environment interactions as cast within the framework of "world models." Reconciling environment with other social and economic objectives entails both regulation, economic incentives, institutions, and finally technological innovations. The article demonstrates the need for a new model of innovation to support the move to a more sustainable pattern of growth. Freeman's article also introduces the second cluster of contributions to this special issue, by addressing the question of which conditions are necessary for realizing (some of) the potentials offered by continuous technological change.

These conditions are reviewed at the theoretical level by Vernon Ruttan in the fourth article. He reviews two models of technical change: path dependence, in which the forces of technological inertia are predominant, and induced innovation, where new factors and criteria have the potential to redirect technological trajectories toward new social objectives. The article concludes that the two models are complementary rather than mutually exclusive, and technological inertia can be overcome to induce a path of technological development and infrastructure investments consistent with the rising (social and economic) value of environmental resources.

These complementarities, and the fact that forces of change can overcome technological inertia (or reinforce it), are illustrated in the following two articles.

For Robin Cowan and Staffan Hulten, technological inertia derives from intraindustry and interindustry sources. The article explores possibilities of escaping from technological "lock-in," a term coined by Brian Arthur [20, 21]. The authors use the example of the electric vehicle to review the potential for change of various "inducing factors," including the emergence of environmental priorities. Vigorous policy support in all possible domains would be necessary to provide the quantum leap from the current entrenchment in the internal-combustion automobile to the electric car.

Jean-Marie Martin, author of the sixth article, explores the driving forces of the evolution of energy-related technologies. The article reminds us that technological change rarely takes the direction anticipated by the proponents of new technologies and that technology evolution must be considered holistically. Improvements in both new and established technologies, along with the institutional environment in which technological change is embedded, need to be considered. Factors of inertia, such as technological interrelatedness, lumpiness of investments, and factors of change, including technological variety, pluralism, and institutional factors, are assessed in their respective contribution to the evolutionary dynamics of energy technologies, and a rationale for policy oriented toward radical change is given. The article, however, reconfirms that structural change in energy systems is a slow process that must be kept in mind especially for (environmental) advocates of a rapid move "away from the carbon atom."

The article by Arnulf Grübler and Nebošja Nakićenović provides a contrasting long-term perspective on the "decarbonization" of the global energy system. The long-term stable patterns of structural change proceed, however, at slow rates, confirming the analysis of Jean-Marie Martin that earlier expectations of a rapid transition away from a carbon-based economy were perhaps premature. Nevertheless, the gradual (although slow) decarbonization trend emerges as an undeniable consequence of continued technological change and changing consumer preferences for more flexible, convenient, and clean energy forms as incomes rise. The article give reasons for cautious optimism, as this development requires "only" a significant acceleration of decarbonization; it does not require a complete departure into an entirely new development paradigm.

Iddo Wernick explores the history and future of the evolution of U.S. material consumption patterns. Wernick identifies a number of indicators that show a slow and gradual "dematerialization" of the U.S. economy. Bulk materials consumption no longer runs in tandem with economic activity in the United States. In spite of a general persistence of main factors driving patterns of materials consumption (including demographic variables and consumer preferences), some factors of change, such as saturated markets and technological innovations, offer promise for reduction in the material and environmental intensiveness of economic activities.

Technology and Environment: Three Major Cross-Cutting Themes

In this section, we present our own interpretative summary of the main issues addressed in the articles of this special issue. The articles run across three lines of argument.

Uncertainty, ignorance, and "dispersed knowledge" are described as a dominant mode of generation and distribution of technological knowledge; this is particularly true for environmental knowledge and problem awareness. An important question addressed in this issue is whether science and policy are moving from a system characterized by unexpected discoveries and (environmental) "surprises" and limits of management attention (policy-making can only deal with a limited number of issues at a time) to a system characterized by a more rational and systematic mode of knowledge acquisition and distribution.

The second question addressed in the articles deals with the tensions between the forces of technological stability and inertia (associated with increasing returns, lock-in effects, and the features of path dependence of large technological systems) and the forces of change, including the role of environment as a possible factor inducing the direction of technological change.

Finally, the articles point to new policy challenges that are emerging. In a nutshell, technology policy must increasingly integrate long-term knowledge acquisition and environmental monitoring, and increasingly feature both mission-oriented objectives (focus on long-term development objectives rather than short-term technology selection) and diffusion-oriented objectives (focus on contextual factors and incentives that steer technology diffusion).

UNCERTAINTY, IGNORANCE, AND DISPERSED KNOWLEDGE

Using the example of nuclear weapons, Schelling shows that unexpected discoveries and research by accident represent a frequently forgotten but important process of learning in a domain where uncertainty and ignorance predominate. Environmental issues are a particularly obvious case. Besides the inevitable factor of limited knowledge, there is an additional factor at work: a systematic bias in the evaluation and information-gathering processes of new technologies that are always assessed according to the characteristics and properties of existing technologies. Environmental issues provide many examples of "discovery by accident": from the impacts of biotic accumulation of DDT to the discovery of an Antarctic "ozone hole" (this latter discovery, in fact, was only made possible by advances in knowledge of stratospheric chemistry and new technologies of measurement and remote satellite sensing).

As a new technology emerges, uncertainties must be dealt with; these uncertainties include not only the technology itself (its current and future properties) but also its possible impacts. These can be classified into three categories: uncertainties of impacts associated with individual uses of the technology; uncertainties associated with the modes of social usage; and uncertainties associated with the (ultimate) magnitude of technology diffusion and thus with (potential) cumulative effects or impacts. For example, when automobiles and railways were first introduced there were concerns over the following questions: what will the health impacts be on railway users (we tend to forget that a number of 19th century medical studies were concerned about the possible health impacts of "excessive" railway speeds of 20 miles per hour)? Will the car remain a curiosity for the rich or gain any social importance, perhaps ultimately replacing all riding horses? Beyond what car-density level might environmental problems such as metropolitan smog emerge? Will the environmental impacts be worse than those of the dominant technology of the day (i.e., horse manure [22])? Uncertainty also pervades the scientific understanding of the mechanisms linking the modes of usage of technologies to environmental problems. Continuing with the automobile example, are environmental impacts proportional to the number of cars on the road? (based on [23] they are not); which types of pollution could emerge that are not known or anticipated at the moment of the introduction of the automobile? Thus, much knowledge must be acquired on a new technology itself, on its possible modes and extent of individual and social use, (environmental) side effects, and so on.

As knowledge and information are progressively acquired, another central problem emerges, that of access to knowledge or what Harvey Brooks describes as the "attention management problem." There is simply a difference between knowledge that may exist somewhere and knowledge that is available in the right form, at the right time, to the right people. Perhaps the greenhouse debate best illustrates such an "attention management problem" as the basic science (as well as order of magnitude forecasts of possible global warming resulting from elevated concentrations of CO_2) has been known, in principle, for exactly 100 years—Svente Arrenhius's classic study [24] appeared in April 1896—and the basic numerical global forecasts have not changed much even with the advent of supercomputers and large general circulation models.

Therefore a central issue relates to the "dispersion" of environmentally and socially relevant knowledge. It remains to be determined whether the attention management problem can be gradually reduced by new technologies of electronic networks, information distribution, or artificial intelligence.

In a more general sense, the first line of arguments encountered in the articles of this special issue is whether we can move from an old pattern of knowledge generation and distribution (the pattern associated with research by accident, ignorance about ultimate uses and diffusion of technologies, and their impacts) and the attention management problem (how to simultaneously deal with numerous emerging environmental and other social priority issues) to a new mode of knowledge generation, assessment, and distribution.

ROLE OF ENVIRONMENT AS AN INDUCING FACTOR FOR CHANGE IN A WORLD CHARACTERIZED BY TECHNOLOGICAL AND INSTITUTIONAL INERTIA

At different levels (technologies, institutions, modes of production and consumption) development trajectories are characterized by path-dependent properties: inertia, persistence, and "lock-in." The articles in this issue provide many examples in the domain of the energy sector, materials consumption, transportation systems, and so on. Different kinds of cumulative processes and positive feedbacks can lead to technological lock-in. This makes the representation of technological change a challenging task. But it is even a greater challenge for devising policies to redirect prevailing (environmentally unsustainable) growth trends and to escape technological and institutional lock-in.

Nevertheless, environment criteria have the potential to change the direction of technical change and to stimulate technological breakthroughs in the design of new systems and the mechanisms through which the relative market shares of competing technologies evolve.

One question addressed in this special issue is: under what conditions can society overcome technological inertia and lock-in to accelerate the transition toward new (but yet uncertain) technological and institutional configurations that are environmentally more compatible? These conditions can be explored at the theoretical level: Vernon Ruttan shows that the economics of path dependence and induced innovation theory could be mutually beneficially combined. They are two elements of a more general framework.

Such conditions can also be explored at the empirical level, and the view put forward by most authors of this special issue on the possibilities of rapid changes in large sociotechnical systems is rather cautious (Robin Cowan and Staffan Hulten, Christopher Freeman, Jean-Marie Martin, and Iddo Wernick). Some of the postulated required changes ("decarbonization" of energy systems or "dematerialization" of materials use) may not entail an entirely new direction, but can build upon long-term evolutionary structural change trends. This view implies a more optimistic perspective, as it does not call for a radical departure from prevailing trends, rather it requires "only" a substantial acceleration of structural changes in a desirable direction (Arnulf Grübler and Nebošja Nakićenović, and also Iddo Wernick).

In summary, environmental criteria can play a role as inducing factors to create incentives for incremental improvements of existing systems. We know, however, that incremental improvements are not enough to achieve the energy and material consumption reductions that may be required to alleviate a number of potential environmental impacts. At present, it is not clear whether the environment along with other inducing factors is strong enough for a technology-led push toward a new "green" technoeconomic paradigm. There is, therefore, need for major policy support to trigger such changes. All the articles in this special issue agree that such far-reaching transformations of sociotechnical systems cannot be implemented within a short time span. Instead, many decades (and for certain infrastructures perhaps even a century) will be required for a complete turnover of capital stock and an entire reconfiguration of the sociotechnical "landscape." The time scale of these sociotechnical changes matches those of some longer-term environmental issues, such as possible climate change. This places additional weight on new modes of information generation and distribution of environmental issues because, by the time sufficient information is gathered to reduce both scientific uncertainty and the policy attention management problem, it may simply be too late to initiate, yet to implement, large-scale system transitions.

TECHNOLOGY POLICY DILEMMAS FOR ENVIRONMENTAL ISSUES

At present it is impossible to develop a clear and concise picture of the policy implications of the above-presented, cross-cutting "meta"-themes of the interactions between technology and the environment. Therefore, we limit our discussion to describing four policy dilemmas; this discussion could serve as a guide for future research. These (somewhat overlapping) dilemmas are between: long-term and short-term environmental objectives; trade-offs between technological innovation and environmental regulation; the dilemma between the need to maintain technological diversity and to promote cost reductions via standardization; and finally possible trade-offs between promoting technology diffusion and maintaining desirable reversibility.

The origin of the first dilemma arises from the fact that the goal of environmentally compatible development requires a wide range of complementary policies to support investments in new environmental technologies and the rapid diffusion of successful applications. Such policies essentially fall into two main areas: policies supporting the generation of long-term technological alternatives and policies to control pollution emissions in the short-term through norms, taxes, and end-of-pipe technologies. Thus, the dilemma deals with the fact that pursuing a short-term strategy of incremental improvements may generate counterinnovative effects, by reducing flexibility and incentives for undertaking technological experiments, ultimately delaying long-term radical changes. End-of-pipe technologies offer definite advantages to private firms because of their greater short-term adaptability in comparison with more radical (cleaner) process innovations; they can be added to existing plants; and they generally involve fewer learning requirements than major process innovations [25]. Under many conditions, they are a rational solution to the need to control pollution emissions from existing plants. As a result of these advantages, policies to encourage environmental innovation can unintentionally support the development of solutions based on end-of-pipe technologies that may be inferior in the long-run in terms of both costs and environmental impacts to "green" plants designed from scratch. In this way, policies can have the effect of accelerating environmental progress in the short-term at the expense of more fundamental and drastic progress in the long-term. Thus, short-term environmental regulatory policies and policies designed to support major technological (and organizational) discontinuities may be contradictory. Strategies of end-of-pipe regulation—which can play a very significant role in short-term emission reduction—can undermine the bases and incentives for more radical changes in the long term.

The second dilemma deals with the fact that environmental regulatory and standard policies can fundamentally alter the innovation behavior and performance of firms. This is due to two factors [19]. First, regulation creates a new risk in the R&D process (in addition to the technical and commercial risks). The risk is that a new product cannot meet both current and future environmental standards. If there is uncertainty about the possibility that more severe restrictions may be imposed in the future, a firm may prefer to impose a moratorium on commercializing new process and product innovations. Second, political reluctance to impose costly measures on industry can lead to discrimination in the implementation of new regulatory standards. In most cases, new industrial facilities or consumer goods are subject to stronger regulations than existing ones. This "grandfathering" principle turns out, in fact to be a punishment of innovators; it can introduce disincentives to allocate resources to R&D and investments. As a result, the conditions and procedures of innovation are changing in industries characterized by strong command-and-control environmental regulation. In particular, the conventional command-and-control regulatory approach does not allow for flexibility to experiment with different approaches and technologies. This is not to say that command-and-control regulations are not necessary to establish high standards. It is to say that in most cases conventional command-and-control regulations preclude major paradigm shifts toward environmentally preferable systems.

The third dilemma is due to the tension between technological diversity and standardization. Policy-makers (and society at large) typically find themselves in situations where they do not fully know the tasks ahead because most environmental issues (and possible remedies to them) are notoriously ill understood. This kind of uncertainty suggests a need to maintain technological diversity in order to maintain a broad range of alternatives, as well as to maintain flexibility as more is learned on a particular environmental issue. Maintaining diversity, however, is a very difficult task because of the constant tendency of technological systems to lose variety, e.g., in the quest for cost reductions through standardization, economies of scale, or shared infrastructures (network externalities).

The last dilemma is between the needs to accelerate the creation and diffusion of environment friendly technologies and the needs to minimize technological irreversibility (in view of potential future "surprises"). When uncertainties about the merits and/or impacts of a technology are high, an attempt to redirect R&D to, or "forced" diffusion of, one of several options before a technology is adequately developed and tested could lead to failure [25]. Such policies could also prematurely narrow the range of solutions that might be willingly explored by private firms. When there is considerable uncertainty about the socially optimal course of technological development, the best policy is to refrain from active intervention and to identify and prepare to take advantage of the next opportunity window for high-leverage intervention. In this respect, policy-making must consider the opportunity costs of supporting any specific technology.

There is, however, a class of technologies that requires support without any ambiguity. These technologies are those classified as research tools, observation and exploration instruments, and decision-making tools ("meta-technologies"). These technologies increase our capabilities of measurement, control, observation, learning, and decision-making. Efforts to develop such technologies may, in fact, also benefit from the "recycling" of military technologies and environmentally relevant data. Examples include oceanographic data collected by and for submarine operations, or the recent MEDEA proposal [26] to use high-resolution military spy satellites for long-term environmental monitoring.

We need more technology, not less, was the credo of various authors writing about environmental problems in the 1970s. To this true proposition could be added that we need above all new modes of generation and distribution of knowledge, flexible regulations, technological diversity, as well as an increase of our observation and learning capabilities on environmental impacts of technologies. In our viewpoint, only new modes of technological learning, "meta-technologies" and new "technologies" of institutions and flexible regulatory frameworks will enable us to better deal with the problems of ignorance, uncertainty, and the complexity of choices that are at stake for supporting the transition to environmental compatibility.

Note Added in Proof

This special issue of *Technological Forecasting and Social Change* aims to shed new light on the interactions between technology and the environment. For a complementary perspective, the reader is also referred to the recent special issue of *Dædalus* [27] and its companion book *Technological Trajectories and the Human Environment* [28].

References

1. Simon, H., Technology and Environment, *Management Science B (Applications)* XIX, (10), 1110-1121 (1973).
2. Rosenberg, N., Technology and Environment, in *Perspectives on Technology*. N. Rosenberg, ed., Cambridge University Press, Cambridge MA, 1976
3. Ruttan, V., Technology and the Environment, *American Journal of Agricultural Economics* 53, 707–717 (1971).
4. Starr, C., and Rudman, R., Parameters of Technological Growth, *Science* 182 (October 26), 358–364 (1973).
5. Forrester, J. W., *World Dynamics,* Wright-Allen, Cambridge, MA, 1971, p. 142.
6. Meadows, D. H., Meadows, D. L., Randers J., and Behrens, W. W., *The Limits to Growth,* Signet, New York, 1972, p. 207.
7. Simon, J. L., and Kahn, H., eds., *The Resourceful Earth: A Response to Global 2000,* Blackwell, Oxford, 1984, p. 585.
8. Cole, H. S. D., Freeman, C., Jahoda, M., and Pavitt, K. L. R., *Models of Doom. Critique of Limits to Growth,* Universe Books, New York, 1973, p. 244.
9. Ausubel, J. H., and Sladovich, H. E., eds., *Technology and Environment,* National Academy Press, Washington, DC, 1989, p. 221.
10. Gray, P. E., The Paradox of Technological Development, in *Technology and Environment*. J. H. Ausubel and H. E. Sladovich, eds., National Academy Press, Washington, DC, 1989.
11. Goeller, H. E., and Weinberg, A. M., The Age of Substitutability, or What Do We Do When the Mercury Runs Out, in *Technological Substitution. Forecasting Techniques and Applications*. H. A. Linstone and D. Sahal, eds., Elsevier, Amsterdam, 1976.
12. Nakićenović, N., Growth to Limits: Long Waves and the Dynamics of Technology, Thesis, IIASA, Laxenburg, Austria, 1984.
13. Ausubel, J. H., Regularities in Technological Development: An Environmental View, in *Technology and Environment*. J. H. Ausubel and H. E. Sladovich, eds., National Academy Press, Washington, DC, 1989.
14. Martin, J.-M., Energy Intensity of Economic Activity in Industrialized Countries: Is the Long-term Evolution Providing Useful Information? *Economies et Societes* 4, 9–27 (1988) (in French).
15. Gilli, P. V., Nakićenović, N., Grübler, A., and Bodda, L., *Technological Progress, Structural Change and Efficiency of Energy Use,* Verbundgesellschaft, Vienna, 1990, p. 331 (in German).
16. David, P. A., and Wright, G., Resource Abundance and American Economic Leadership, CEPR Publication No. 267, Stanford University, Stanford, CA, 1991.
17. Freeman, C., and Perez, C., Structural Crises of Adjustment, Business Cycles and Investment Behavior, in *Technical Change and Economic Theory*. G. Dosi, C. Freeman, R. Nelson, G. Silverberg, and L. Soete, eds., Pinter Publishers, London, 1988.
18. Meadows, D. H., Meadows, D. L., Randers, J., *Beyond the Limits: Global Collapse or a Sustainable Future,* Earthscan, London, 1993, p. 300.
19. Eads, G., Regulation and Technical Change: Some Largely Unexplored Influences, *American Economic Review* (70)2, 51–54 (1980).
20. Arthur, W. B., On Competing Technologies and Historical Small Events: The Dynamics of Choice under Increasing Returns, WP-83-90, IIASA, Laxenburg, Austria, 1983.
21. Arthur, W. B., Competing Technologies: An Overview, in *Technical Change and Economic Theory*. G. Dosi, C. Freeman, R. Nelson, G. Silverberg, and L. Soete, eds., Pinter Publishers, London, 1988.
22. Montroll, E. W., and Badger, W. W., *Introduction to Quantitative Aspects of Social Phenomena,* Gordon and Breach, New York, 1974, p. 349.

23. Brooks, H., The Typology of Surprises in Technology, Institutions and Development, in *Sustainable Development of the Biosphere*. W. C. Clark and R. E. Munn, eds., Cambridge University Press, Cambridge, UK, 1986.
24. Arrenhius, S., On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground, *Philosophical Magazine and Journal of Science,* Fifth Series, April, 237–276 (1896).
25. Soete, L., and Arundel, A., eds., The Long-Term Challenge: Environmentally Sustainable Development, in *An Integrated Approach to European Innovation and Technology Diffusion Policy,* Chap. 3. SPRINT, European Community Programme for Innovation and Technology Transfer, Brussels-Luxembourg, 1993.
26. Beardsley, T., Environmental Secrets – MEDEA Brings Intelligence in from the Cold, *Scientific American,* July, 19-20 (1995).
27. The Liberation of the Environment, *Dædalus* 125(3), Summer (1996).
28. Ausubel, J. H. and Langford, H. D., eds., *Technological Trajectories and the Human Environment.* National Academy Press, Washington, DC, (in press).

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