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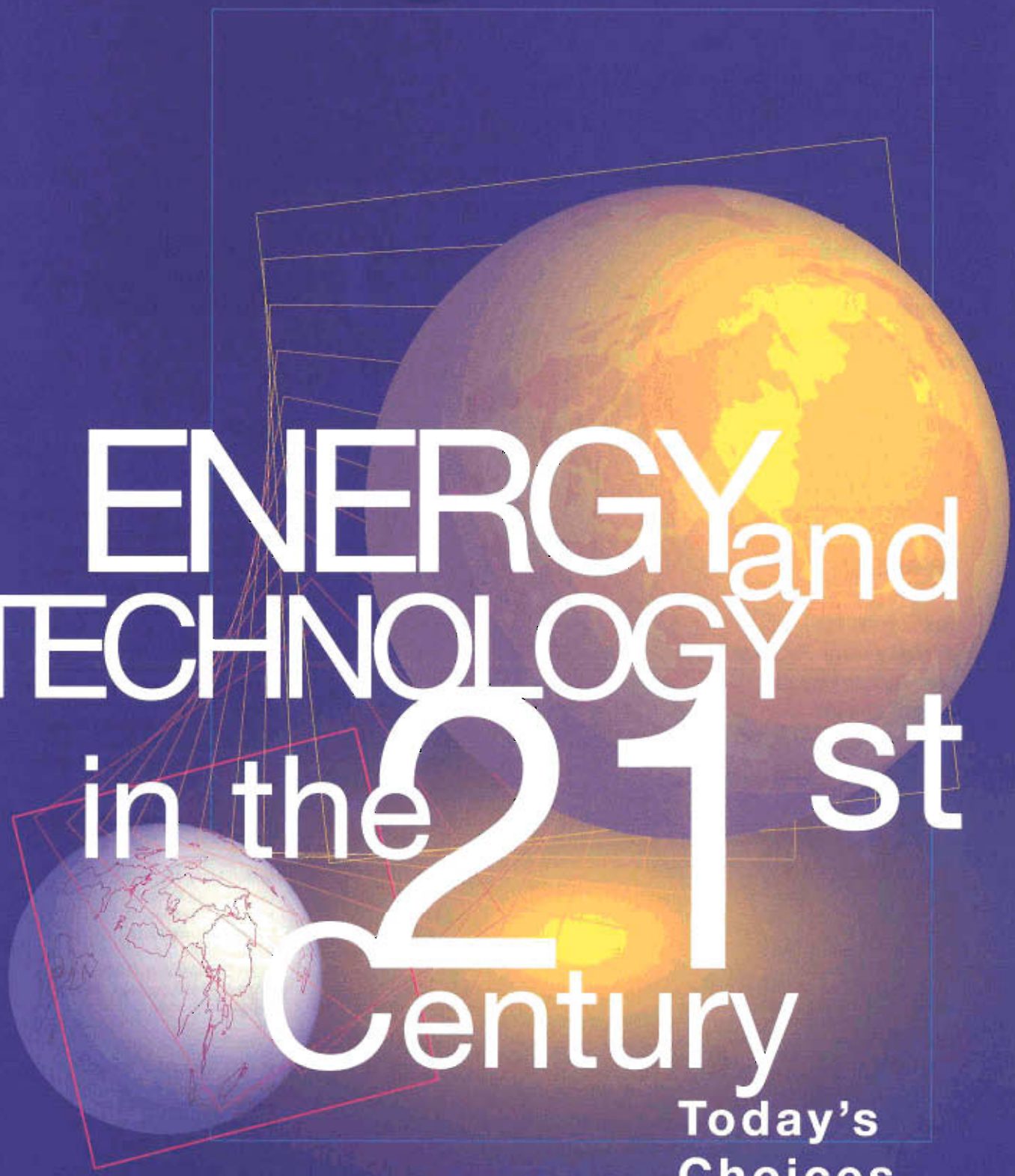

ENERGY and TECHNOLOGY in the 21st Century

Today's Choices Determine Tomorrow's Options

Contents

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Options is a magazine featuring the activities of IIASA, located in Laxenburg, Austria. IIASA is an interdisciplinary, nongovernmental research institution sponsored by a consortium of National Member Organizations in Asia, Europe and North America. The Institute's research focuses on sustainability and the human dimensions of global change. The studies are international and interdisciplinary, providing timely and relevant insights for the scientific community, policy makers and the public.

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Editor: Mary Ann Williams
Contributing Editors:
Margaret MacDonald,
Christoph Schneider
Design/DTP:
Peter D. Reisinger–Grafic-Design
Printed by Holzhausen, Vienna

IIASA
A-2361 Laxenburg, Austria
Phone: +43 2236 807
Fax: +43 2236 71 313
E-mail: inf@iiasa.ac.at
Web: www.iiasa.ac.at

IIASA

Energy and Technology in the 21st Century

During last fall, Cambridge University Press published two groundbreaking books reflecting aspects of the work conducted by IIASA's Environmentally Compatible Energy Strategies (ECS) project.

One of these books, *Global Energy Perspectives*, edited by Nebojša Nakicenovic, Arnulf Grübler, and Alan McDonald, has already attracted worldwide attention since its presentation at the World Energy Congress in September 1998. Based on the results of a five-year collaborative study with the World Energy Council, the book outlines scenarios that will form the basis of national and international energy projections for years to come. Future energy options for a more populated, economically developed world will reflect consumer demand for cleaner, more flexible, and more convenient energy end uses. However, the book concludes that the number of options available will depend on technological investments made over the next two decades.

Also in September, Cambridge University Press published a second book reflecting ECS work. *Technology and Global Change*, by Arnulf Grübler, marks another important event in IIASA's history and deserves wide attention.

Over the past two decades, IIASA's research has made many important contributions to understanding the interactions between environment and technology. As a result, IIASA has become well known for its work on technological dynamics, evolutionary economics, and global environmental change. But Grübler's book goes beyond analysis of a single issue, and documents insights gained from a true interdisciplinary perspective. His work illustrates one of IIASA's continuing—but often unrecognized—strengths: its capability to bring the knowledge from multiple disciplines to bear on its research.

Grübler emphasizes the role of technology as both a source of global environmental change and a mitigator of its effects. Technology relates to all major drivers of global change, such as population growth, economic development, and resource use. But technology is also central in monitoring environmental impacts and implementing response strategies. The book draws heavily on Grübler's own extensive research on the topic, but also reflects earlier work carried out at IIASA by a number of other leading scholars. Twenty years ago, Cesare Marchetti and Nebojša Nakicenovic started their highly influential work on the dynamics of technological substitution. Shortly thereafter, the joint research of Brian Arthur and Yuri Ermoliev led to a deeper understanding of competing technologies. Tibor Vasko and Chris Freeman examined the relationship of technology to the theory of long waves in the world economy. Giovanni Dosi and his colleagues applied evolutionary economics to questions of technological development. More than 20 years ago, Bill Nordhaus initiated his pioneering studies on the economics of climate change; he continues close collaboration with IIASA colleagues on issues of induced technical change. The above are only a few examples of how IIASA has contributed to the theory of technological dynamics, to the understanding of how technology evolves, and how these relate to environmental change.

Grübler presents many examples of the value of interdisciplinary research. Compartmentalization of science in analyzing global change can miss important interdependencies or joint causes of global change that cut across different sectors and environmental media. The book also effectively illustrates Grübler's personal conviction that more effectively harnessing technological change to our evolving social and environmental aims is a worthwhile goal.

I personally hope that both *Global Energy Perspectives* and *Technology and Global Change* reach a wide audience. If they do, the important work carried out at IIASA, and the Institute's unusual, multidisciplinary approach, will become better known and appreciated around the world.

Dr. Gordon J. MacDonald
IIASA Director

Research Updates

IIASA Model Projects Emissions of Long-Lived Gases

The Kyoto Protocol to the Framework Convention on Climate Change requires industrialized nations to limit their emissions of sulfur hexafluoride (SF_6) and of two perfluorocarbons (PFCs), perfluoromethane and perfluoroethane. Although their contribution to global warming is minor, especially compared to that of carbon dioxide, these gases pose a danger because they persist in the atmosphere for tens of thousands of years. At present, few data exist on the emission sources for these gases, and no research has hitherto projected the trends in emissions or studied the implications of alternative policy approaches to achieving reductions.

IIASA Director Gordon MacDonald and ECS staff member David Victor have developed a simple spreadsheet model for projecting future emissions and analyzing compliance with regulatory commitments. For each gas, they gathered data from atmospheric measurements and engineering studies, computed the average annual global source from the observed increase in atmospheric concentrations, attributed that source to the industrial activities known to yield the emissions, and derived emission factors for the most recent years for which reliable data are available. The model then projects future emissions, atmospheric concentrations, and radiative forcing for two scenarios reflecting different policy approaches to achieving reductions.

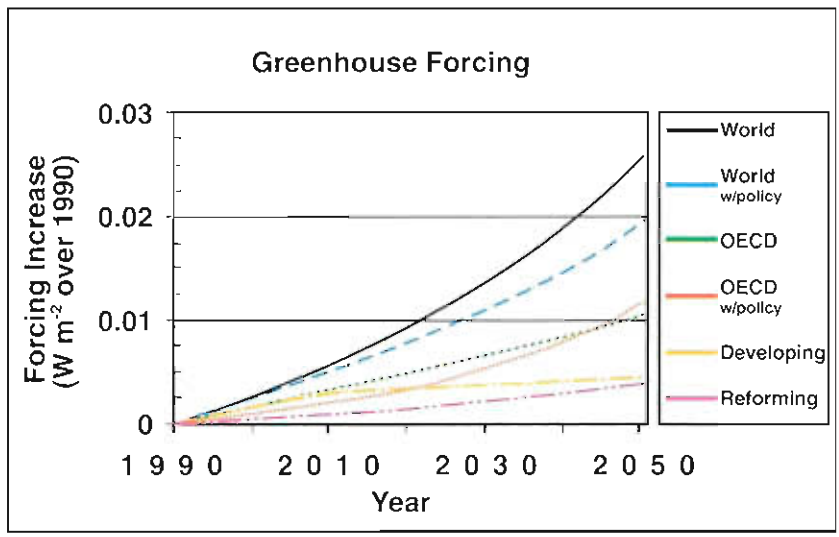
The model permits analysis according to three major regional groupings: OECD member nations, the "reforming" industrialized countries, and the developing world. The designers based the model on the fundamental principle that the estimated regional emissions must add up to the observed global rise in atmospheric concentration. They tuned the model to reproduce data from the United States, the only large economy for which it is possible to estimate data for both PFC sources: aluminum and semiconductor production. SF_6 emissions result primarily from electricity production and magnesium casting.

IIASA's baseline scenario assumes that OECD nations do no more than fully implement existing low- and negative-cost policies to regulate emissions of PFCs and SF_6. Even this minor move would result in a 50 percent reduction over 1990s emission levels by the year 2010, and cut the projected radiative forcing by a quarter. The policy scenario assumes that emission factors in OECD nations decline to one-tenth of current levels over 15 years, beginning in 2000.

Given the current lack of reliable data, industrialized countries could seemingly meet their obligations to regulate these long-lived gases if they report high emissions in the baseline year (1990 or 1995), and then select low emission factors for subsequent control years, leading to large artificial "reductions." IIASA's modeling research demonstrates the urgent need for more complete and reliable data sets and improved modeling methods to ensure that treaty compliance leads to genuine reductions in substances whose impact on the atmosphere would last as long as human civilization.

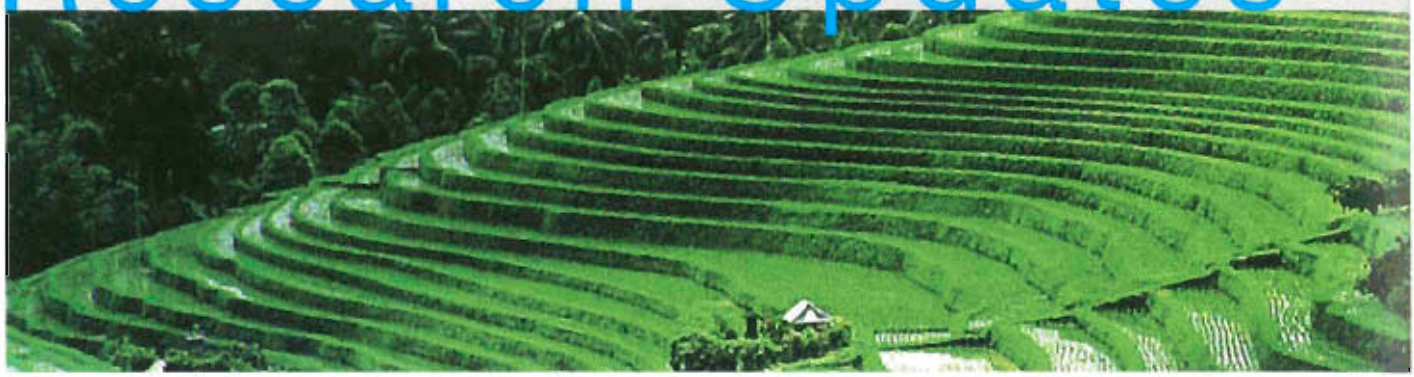
For more information, or copies of the model, contact:
Gordon J. MacDonald:
e-mail: macdon@iiasa.ac.at

Radiative forcing due to SF_6 and PFCs



Curves show total forcing due to the accumulated emissions of these gases. The study uses the forcing coefficients summarized by the Intergovernmental Panel on Climate Change and ignores band saturation, which is not significant at such low concentrations.

Research Updates



The Balance of Cultivated Land in China during 1988-1995

Chinese farmers are cultivating more land than traditionally thought, which may be good news for China's future food prospects. Drawing upon improved and detailed survey information by China's State Land Administration (SLA), a study by IIASA's Land Use Change (LUC) project has confirmed that the amount of cultivated land in China is much higher than has traditionally been reported by the country's State Statistical Bureau. At the same time however, China is actually experiencing a progressive loss of farmland due to economic and environmental factors. LUC's research has greatly improved the understanding of the magnitude and actual usage of farmland in different regions of China between 1988 and 1995.

Over its long history, China has met its food needs from a large base of fertile agricultural land. Between 1949 and 1959, the cultivated area rapidly increased due to large-scale reclamation of arable land, along with the development of the national economy. Poor documentation of land use in the 1960s and 1970s has resulted in misleading information regarding the level of cultivated land in China. However, due to the massive population growth during the last decades, cultivated land has become a critical and scarce production factor in agriculture.

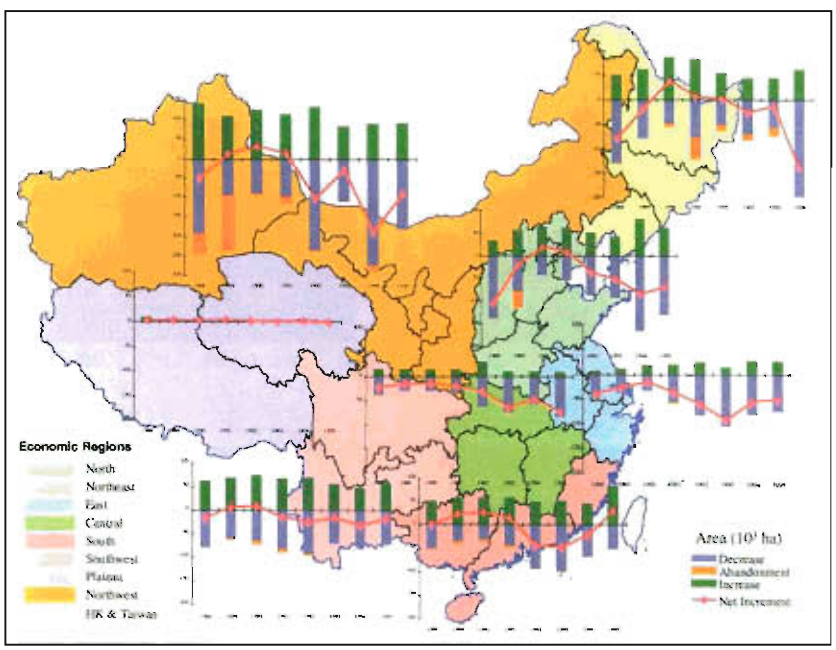
For the end of 1995, LUC estimates the total cultivated land at 131.1 million hectares, accounting for about 14 percent of China's whole territory. Between 1988 and 1995, the balance of cultivated land was characterized by a net loss of farmland amounting to about 1.7 million hectares. This difference results from land reclamation, which added some 3.1 million hectares to the cultivated land base, as well as from diversions to other uses of about 4.8 million hectares. Furthermore, the potential for developing additional arable land in China is fairly limited and costly. The SLA currently estimates the total extent of undeveloped land with cultivation potential to be less than 13.3 million hectares.

It is therefore of great concern to monitor and understand the tendency of changes in China's cultivated land base, and to increase awareness by both the public and decisionmakers of the urgent need to protect high-quality farmland in a period of social change and rapid economic development. Unlike other major food producing countries, such as the United States, the best agricultural areas in China are also the most densely populated. Unchecked conversion of farmland for infrastructure, industrial and residential expansion in rapidly developing regions may cause unnecessary and irreversible damage to the agricultural land base.

For more information, contact:
Günther Fischer,
e-mail: fisher@iiasa.ac.at

For a more detailed description of LUC's research, please visit the project's web site at: www.iiasa.ac.at/Research/LUC.

Change of cultivated land in LUC economic regions of China during 1988–1995



The line graphs show the net increases in farmland (excluding abandonment). The figure indicates that after 1992 practically all regions have had a negative balance of cultivated land, i.e., net farmland losses.

Energy in the 21st Century

Today's Choices Determine Tomorrow's Options

The range of future energy supply possibilities—coal, oil and gas, nuclear, and renewables—seems wide open today. By 2020 it will have narrowed considerably. What will make the difference is how countries and industries target their technological research, development, and demonstration (RD&D) in the meantime. It can take 40 years for new energy technologies to diffuse into widespread use, and because costs decrease and performance improves with experience, technologies that get the quickest start down their learning curves can often lock in their initial advantage. Thus, early investments in technology RD&D, how quickly these investments increase, and where they focus will determine both the pace of worldwide economic growth and the extent of environmental protection. Of six scenarios developed in a joint study by IIASA's Environmentally Compatible Energy Strategies (ECS) project and the World Energy Council (WEC), "muddling through" on our present course offers the least attractive future.

Those were the main messages presented by ECS to energy industry executives and energy ministry officials at the 17th WEC Congress on September 15. The Congress, held in Houston, Texas, attracted some 5000 energy experts from almost 100 countries, including 35 energy ministers. Nebojša Nakićenović, Arnulf Grübler, Sabine Messner, David Victor, Alan McDonald, and Manfred Strubegger of ECS joined WEC officials in a special session to describe the five-year IIASA-WEC study in detail. ECS had presented interim results three years earlier in a similar special session at the 16th WEC Congress in Tokyo. The Houston Congress also provided the occasion for an advance release of the book *Global Energy Perspectives*, which presents the final study results, and distribution of a CD-ROM multimedia study summary prepared by ECS and the University of Siegen. Information on the CD-ROM is included on page 11.

Communicating with Government and Industry

WEC is the world's leading non-governmental energy policy forum. It has member committees in 94 countries that represent over 90 percent of world energy consumption. Membership in the committees includes the full range of energy industries, banks and financial institutions, equipment manufacturers, engineering companies, and major energy consumers.

ECS' collaboration with WEC began in 1993, after WEC had completed a study of possible global energy futures through 2020. Because of the long lifetimes of power plants, refineries, and other energy investments, however, there is not a sufficient turnover of such facilities to reveal large differences in alternative energy scenarios prior to 2020.

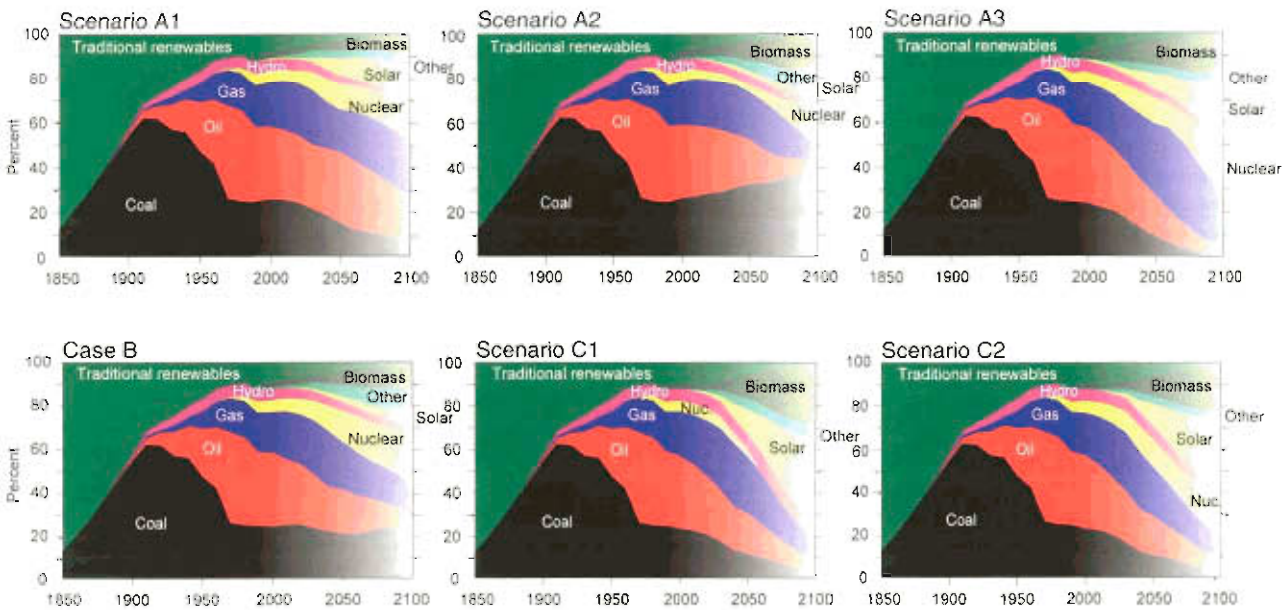


Figure 1: Evolution of primary energy shares, historical development from 1850 to 1990 and in six scenarios to 2100.

All scenarios look much the same for the next few decades, and all rely heavily on fossil fuels. But investments between now and 2020 will make a big difference in how global energy development unfolds after 2020. To evaluate these impacts and assess alternative near-term investment strategies, scenarios extending beyond 2020 are needed. WEC turned to IIASA to provide essential expertise in long-term global energy scenarios.

The collaboration was attractive to IIASA because it met the Institute's objectives of (1) staying at the leading edge of research on long-term global energy scenarios; (2) working closely with the users of such research; and (3) ensuring that results are widely and effectively disseminated to influential decision makers in both the private and governmental sectors.

Technological Learning and Early Investment

The IIASA-WEC study extended the time horizon from 2020 to 2100 and analyzed three cases of possible future developments, subdivided into six scenarios. The six scenarios (*Figure 1*) cover a wide range—from a tremendous expansion of coal production to strict limits, from a phaseout of nuclear energy to a substantial increase, and from carbon emissions in 2100 that are only one-third of today's levels to increases by more than a factor of three. Yet for all the variation explored on the supply side, all scenarios managed to match the expected demand for more flexible, more convenient, and cleaner forms of energy (*Figure 2*). None was limited by the exhaustion of any category of energy resources, nor did any require unprecedented investment rates. Total estimated energy investments between 1990 and 2020 ranged from $9 to $15 trillion in the scenarios, but remained less than 1.5 percent of world GDP.

Differences among the scenarios are due principally to different assumptions about the amount and focus of investments in technological RD&D, particularly investments between now and 2020. Case A, comprising Scenarios A1, A2, and A3, for example, incorporates rapid technological progress and high economic growth, particularly in developing countries. In Scenario A1 progress is fastest in oil and natural gas technologies, resulting in high future availability of oil and gas resources. In Scenario A2, more rapid technological progress in coal technologies, coupled with more limited oil and gas resources, results in a massive return to coal. In Scenario A3 technological investments are focused on nuclear and renewable energy technologies, leading to a phaseout of fossil fuels for economic reasons rather than because of resource scarcity.

Case B includes only one scenario, which describes a future with less ambitious technological improvements and consequently less economic growth. Case B's more modest energy demand and slower technology improvements result in the greatest reliance on fossil fuels of any of the scenarios except the coal-intensive Scenario A2.

Case C presents a "rich and green" future. Its two scenarios include both substantial technological progress focused on non-fossil resources and unprecedented international cooperation centered explicitly on environmental protection and international equity. Both scenarios incorporate policies to reduce carbon emissions in 2100 to 2 gigatons of carbon (GtC) per year, one-third of today's level. Scenario C1 assumes that nuclear power is phased out by the end of the 21st century, while in Scenario C2 a new generation of small, safe nuclear reactors finds widespread social acceptability.

In all six scenarios technological change lies at the heart of productivity increases and economic growth. All six reflect historical patterns of technological "learning," i.e., improvements in performance and reductions in costs as industries gain experience with new technologies. They differ in terms of which technologies benefit most from investment, gather experience most quickly, and thus improve most rapidly. Taken as a group, however, the six scenarios demonstrate two important implications of technological learning. First, as a result of learning effects, currently uneconomic technologies can become economic and widespread within the 100-year time horizon of the study. Second, as experience with early technological innovations improves their cost and performance, late-starting alternatives have increasing difficulty catching up. Future developments are partially locked in to the direction set by early innovations.

Near-term investments, therefore, are critical in determining the long-term future, even if the long lifetimes of energy facilities mean that through 2020 there is little difference among the six scenarios in terms of the mix of resources that they use. It is such near-term investments that will determine which technologies get a head start down their learning curves and are most attractive to consumers when the time does

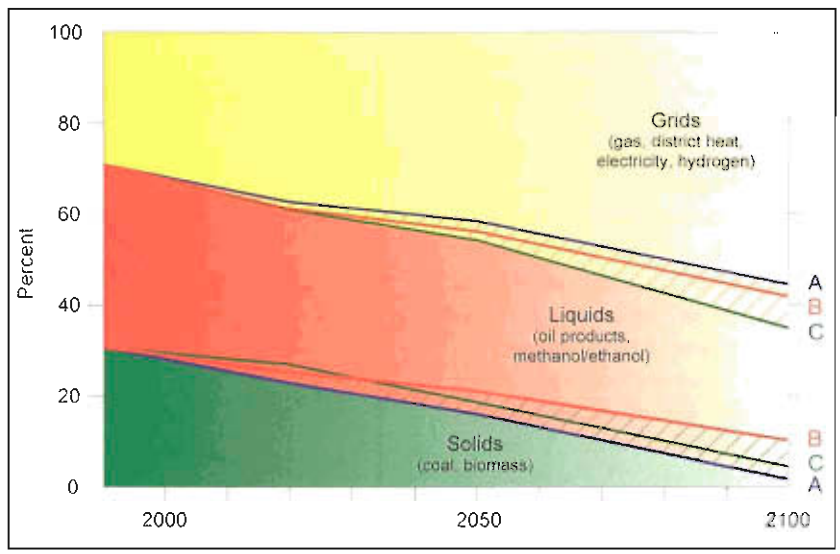


Figure 2: World final energy by form, in percent. By 2100 there is almost no direct final use of coal or fuel wood in any scenario. Coal and biomass are instead converted to electricity, district heat, or synthetic gaseous and liquid fuels.

come to replace old facilities. *Figure 1* shows how modest differences in near-term progress among technologies are magnified after 2020 as the next generation of technologies moves into widespread use.

Climate Change: The Importance of the Long Term

Global results can mask important regional differences. An example is given in *Figure 3*, which shows how the six scenarios measure up to the standards negotiated in the December 1997 Kyoto Protocol to the Framework Convention on Climate Change. The Kyoto Protocol divides the world into Annex I countries—essentially the members of the OECD plus many former Soviet bloc countries in transition to market economies—and non-Annex I countries, which include all developing countries. For Annex I countries the Kyoto Protocol limits aggregate emissions of six of the greenhouse gases that might cause climate warming—carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halocarbons, perfluorocarbons, and sulfur hexafluoride—specifying different emission limits for different countries. Taken together, these would reduce the Annex I countries' average annual greenhouse gas emissions between 2008 and 2012 to about 5 percent below 1990 levels. This is shown as the purple line in *Figure 3* labeled "Kyoto Commitments Annex I."

Figure 3 shows that only the two Case C scenarios would unambiguously comply with the protocol. None of the other scenarios is directly in compliance, but Case B and Scenario A3 come close, at least if all Annex I countries are considered as a group. What makes compliance a possibility in Case B and Scenario A3 is the decrease in carbon emissions in the former Soviet Union (FSU) in the 1990s as a result of severe economic recession. This is shown in the small insert in *Figure 3*. In the Russian Federation and Ukraine, 1997 emissions were already some .31 GtC below the Kyoto limits. In 2010, for the FSU as a whole, the gaps are about .12 GtC in Scenario A3 and .28 GtC in Case B, a difference sometimes referred to as the "Russian bubble." The label purposely emphasizes that the bubble is temporary and will most likely disappear as energy consumption in Russia increases with economic recovery.

By itself the Russian bubble does not lead to compliance with the Kyoto Protocol in Case B and Scenario A3, because the protocol sets limits for individual countries, not for the Annex I countries as a group. But the protocol also provides, in principle, for "emission trading." Emission trading would allow Annex I countries below their Kyoto emission limits to sell their unused "emission rights" to other Annex I countries. Together, emission trading and the Russian bubble could bring scenarios A3 and Case B close to compliance. The 4th Conference of the Parties in

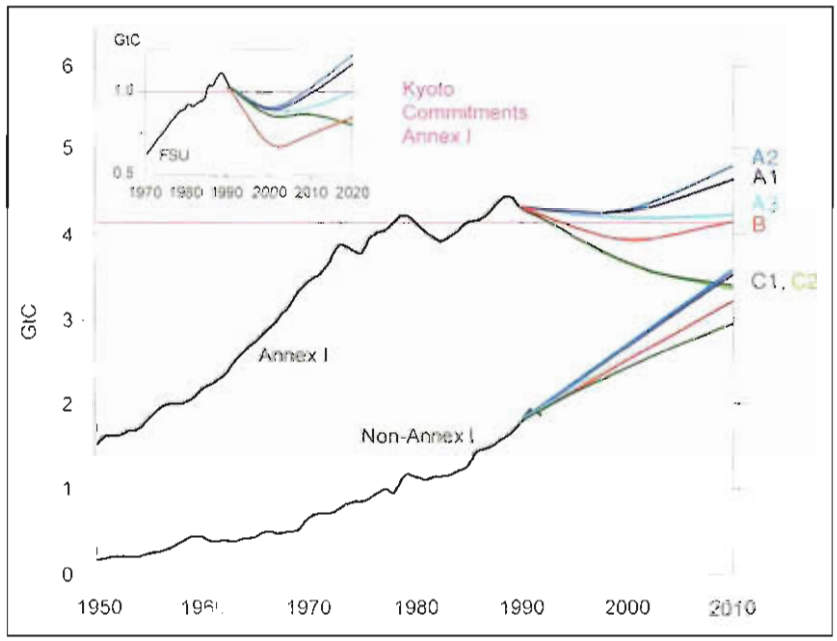


Figure 3: Net energy-related carbon emissions, in GtC. Also shown is the aggregate Annex I emission limit of the Kyoto Protocol. The insert shows emissions in the newly independent states of the former Soviet Union (FSU) compared with the Russian Federation's and Ukraine's 1990 Kyoto limits.

Buenos Aires in November 1998 established a schedule for working out the formal details of emission trading rules by 2000.

Such emission trading by itself would be a short-term response to a long-term problem. *Figures 4* and *5* show that global emissions in Case B climb steadily after the 2008-2012 "budget period" of the Kyoto Protocol, and the atmospheric CO_2 concentration and global temperature follow suit. Partly this is due to large and steady increases from developing countries, none of which is limited by the Kyoto Protocol. Partly it is due to the bursting of the Russian bubble as economic recovery eventually succeeds the 1990s' recession.

Scenario A3 is slightly more complicated. Carbon emissions increase initially but, as a result of significant structural change in the energy supply system, they peak in 2060 and drop to 6 GtC by 2100, roughly the level of 1990 emissions (*Figure 4*). If emissions were to continue to drop after 2100, Scenario A3's atmospheric CO_2 concentration could stabilize at below 550 ppmv, not as good as in Case C, but much better than Case B and Scenarios A1 and A2 (*Figure 5*).

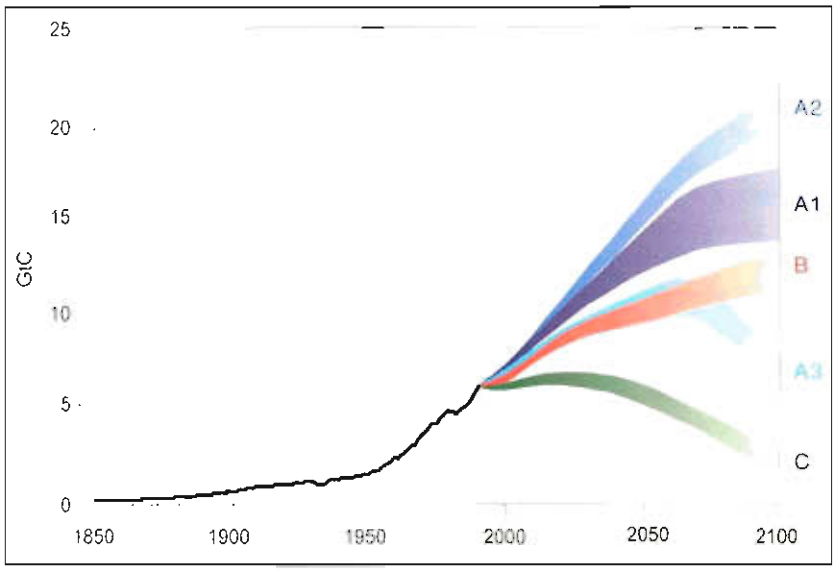


Figure 4: Global carbon emissions from fossil fuel use, 1850 to 1990, and for scenarios to 2100, in GtC. For each scenario, the range shows the difference between gross and net emissions.

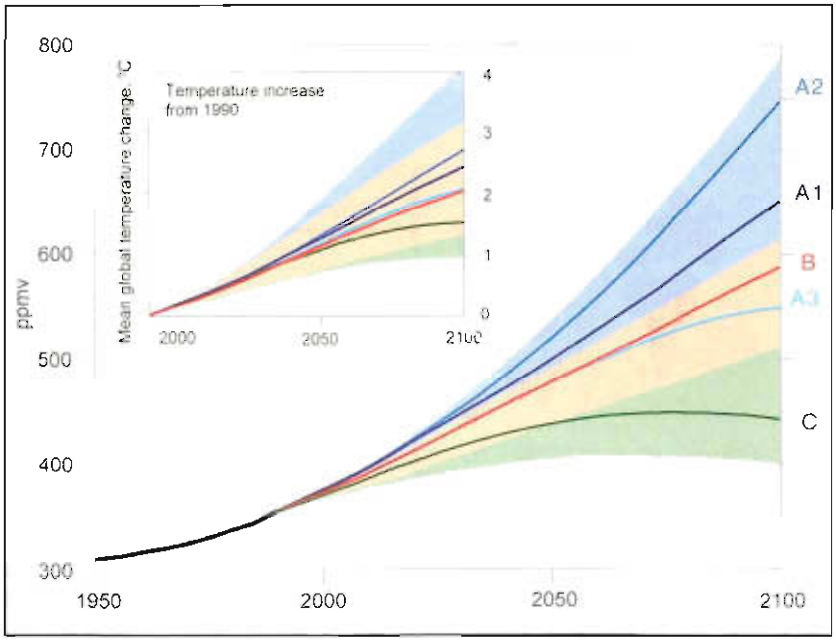


Figure 5: Atmospheric CO_2 concentrations, in ppmv, historical development from 1950 to 1990 and in scenarios to 2100. Insert shows global mean temperature change compared with 1990, in degrees Celsius. The substantial model uncertainties are also indicated.

If a long-term solution to potential climate warming is to be reached, negotiators will have to expand the agreements they reached in Kyoto in three directions. First, they must include limits on the rapidly growing emissions of non-Annex I countries as shown in *Figure 3*. Second, they will have to extend emission limits beyond the 2008-2012 period covered by the Kyoto Protocol. Third, they must fashion agreements with incentives that accelerate technological progress, particularly in the non-fossil technologies featured in Scenario A3 and Case C. Of the six IIASA-WEC scenarios, only these offer a long-term solution to potential climate warming. Indeed, if we are to raise living standards in the developing world and provide for 4 to 6 billion more people by 2100, the only plausible long-term strategy is to greatly improve technology.

Successfully extending emission limits in both time and space (i.e., beyond 2012 and to all countries) will increase incentives to speed technological progress. But an additional mechanism worth consideration is earmarking revenues from emission trading, and from other "flexibility mechanisms" in the Kyoto Protocol, for investments in clean technology. Conditions could be attached, for example, to the $100 billion the OECD might spend on unused Russian and Ukrainian emission rights. Specifically they might require that Russia and Ukraine invest revenues from emission trading in new natural gas pipelines to create Asian alternatives to current coal-intensive development plans. This could set Asia on a cleaner long-term development path, leverage a short-term Russian and Ukrainian windfall into long-term revenues from gas sales, and make the prospect of a $100 billion transfer to Russia and Ukraine more politically palatable.

Regional Perspectives

In addition to global aggregate results, such as those shown in *Figures 1–5*, the IIASA-WEC study presents separate results for the 11 world regions defined in *Figure 6*. In the course of the study, 11 expert regional groups reviewed the regional results. Regional experts were also asked to rate the importance of eight issues central to energy policy debates: population growth, demand for commercial energy supplies, technology, financing, institutional deficiencies, efficiency and conservation, local environmental concerns, and possible climatic change. Issues were scored according to the following scale: 1 = very important; 2 = important; 3 = of concern; and 4 = of no concern. The results are shown in *Table 1*.

In many respects, *Table 1* confirms conventional wisdom. But it also holds some surprises. Considering all 11 regions together, institutional deficiencies and financing are the top concerns. Even North America (NAM), often considered an institutional role model, ranked institutional deficiencies as a top priority. For all 11 regions as a group, possible climatic change appears at the bottom of the list. In general, this issue is of more concern to the OECD regions than to either the developing or reforming regions. All regions ranked local environmental concerns higher than or equal to possible climate change. Western Europe (WEU) lives up to its green image, being the only region to give local environmental concerns a number-one ranking, whereas NAM is unique in scoring technology as a number-one issue.

While population growth is generally of greater concern in developing regions than in reforming or OECD regions, it was also ranked relatively highly by Pacific OECD (PAO). However, the reason is Japan's concern about too *little* population growth, exactly the opposite of the developing regions' concerns. PAO's top ranking for efficiency and conservation, and NAM's top ranking for technology, reflect the two regions' positions on the cutting edge of these fields. Given the importance of technology, efficiency, and conservation in the scenarios, the continuing high priority given to these issues is reassuring.

Next Steps Now

The good news from the ECS Special Session in Houston is that the study's main messages found wide acceptance. The energy experts attending the meeting recognized technological progress as the key to raising living standards in the developing world and providing for 4 to 6 billion more people by 2100, and acknowledged early investments as essential in setting the world on a clean and productive path. The bad news is that actions lag behind good intentions. Both public and private investments in technology have decreased during the last decade, and current investment levels are not reassuring. The world must take far more decisive steps if we are to do better than follow by default the muddling-through scenario represented by Case B. It is the least attractive of all six scenarios, if for no other reason than that it leaves the developing world furthest behind. ■

For more information about ECS visit its web site at www.iiasa.ac.at/Research/ECS

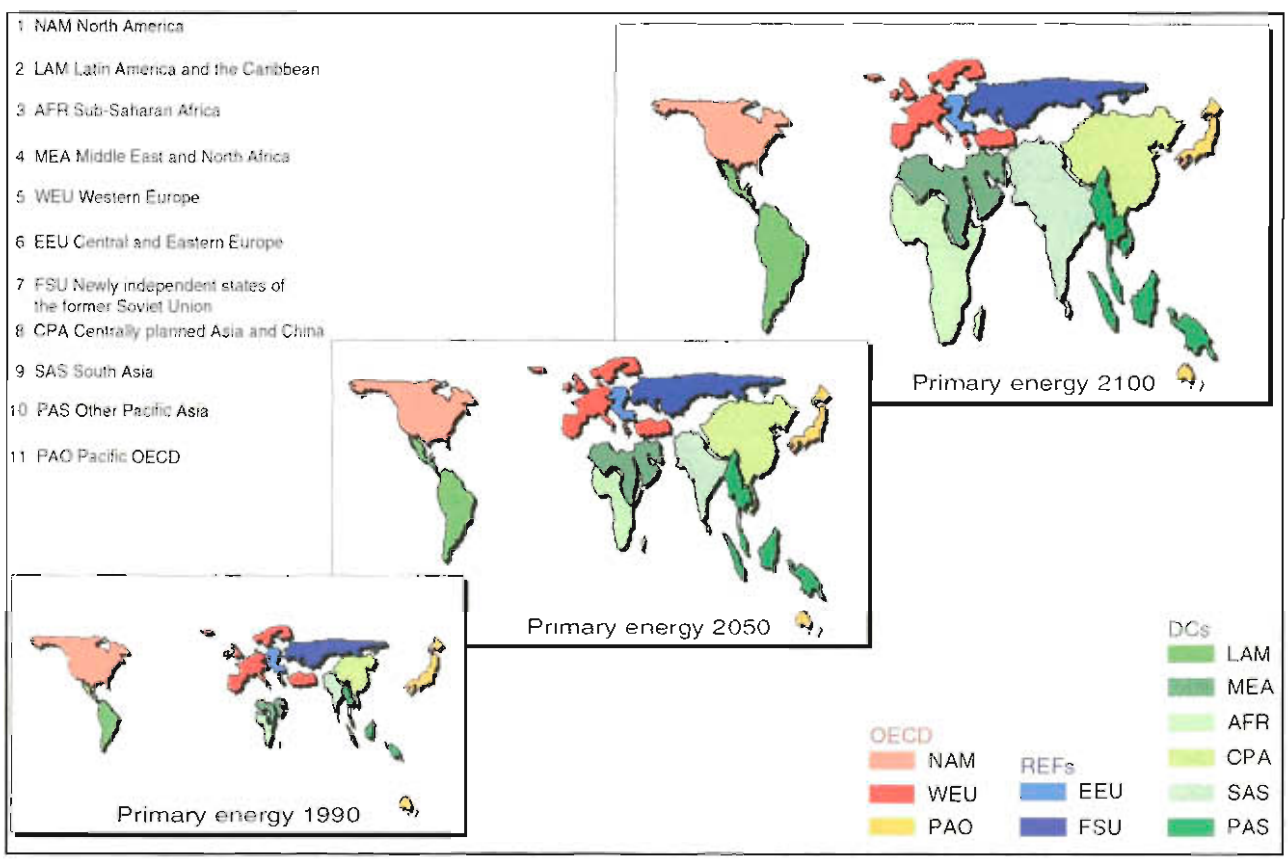


Figure 6: The eleven IIASA-WEC study regions. The figure also shows the changing geography of primary energy use for Case B. The areas of the eleven regions are proportional to their relative shares of global primary energy use in 1990, 2050, and 2100.

Table 1: Regional poll results

See Figure 6 for regional acronyms.

Region	Population growth	Demand for commercial energy supplies	Technology	Financing	Institutional deficiencies	Efficiency and conservation	Local environ-mental concerns	Possible climatic change
NAM	4	3	1	4	1	3	2	2
LAM	2	2	2.5	1.5	2	2	2	2.5
WEU	3.5	3	2	3	2	2	1	2
EEU	4	2.5	2.5	1.5	2	1.5	2	3.5
FSU	4	4	3	1	1	2	3	4
MEA	1	3	2	1	1	3	3	4
AFR	1.5	3	2.5	1.5	1.5	3	2.5	3
CPA	1	2	2	1	1	1	2	2
SAS	2	1.5	2	1.5	1	2	1.5	4
PAS	3	1	2.5	1.5	2.5	2	2.5	3.5
PAO	2	2.5	1.5	2	2.5	1	1.5	1.5

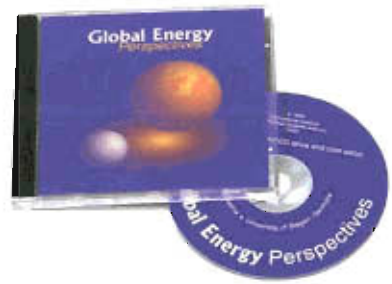
Scoring system: 1 = very important; 2 = important; 3 = of concern; and 4 = of no concern.

IIASA-WEC Research Results Available Electronically

The results of the collaborative work by IIASA's Environmentally Compatible Energy Strategies project and the World Energy Council are available via two highly interactive formats, as well as in the book *Global Energy Perspectives*.

One is through the project's web site(www.iiasa.ac.at/Research/ECS), where users can find summaries of the book's scenarios, regional reviews, and conclusions. Also available through the web site is an interactive database containing the most important numerical assumptions and results of the study.

As a companion piece to *Global Energy Perspectives*, ECS and the University of Siegen have produced a CD-ROM summary of the study that uses animated, colorful graphics to communicate the study's highlights in a way that's understandable even to non-energy specialists. It includes a five-minute "Guided Tour" of the study's key results, but also allows users to peruse all aspects of the study in whatever order they prefer. The CD offers immediate access to the ECS online database, as well as information about IIASA, WEC, and the University of Siegen.



The Global Energy Perspectives CD-ROM costs US $10 (for shipping and handling, payable by Mastercard or Visa). Please use the order form below and send to:

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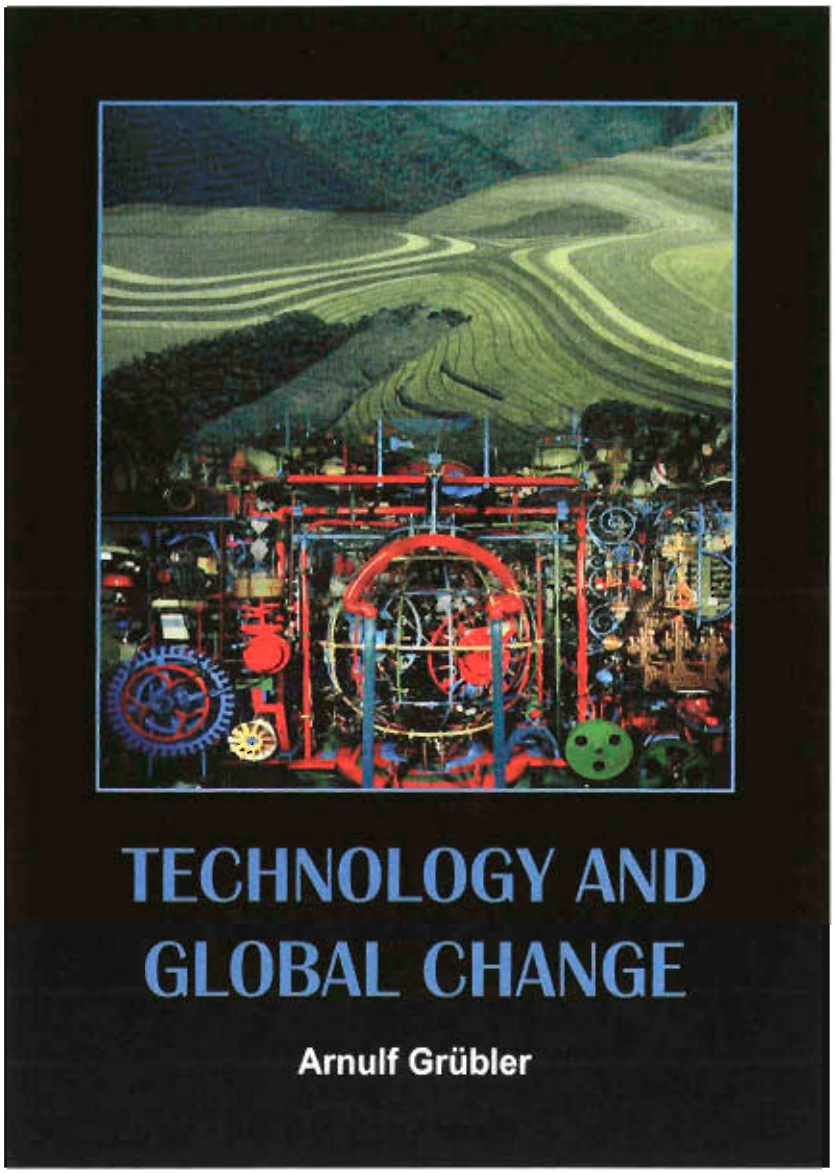
From Bikes to Bytes:

The Past and Future of Technology and the Environment



The cover figure contrasts technology and the environment. At the top are forests—unmanaged ecosystems undisturbed by humans and technology. In the middle are fields, illustrating agriculture's distinction as the oldest technology to transform the environment. (Agriculture is also the technology that has made it possible for us to multiply to close to 6 billion people.) At the bottom is technology, symbolized by a machine. But it is a special kind of machine, designed by a farmer in Austria as a piece of art. As such, it recalls the origin of the word "technology," which comes from the Greek word techne, *meaning art.*

IIASA's recent book *Global Energy Perspectives* (see page 6) reaches the principal conclusion that technology, and technological progress, are the keys to shaping our energy future. Perspectives differ about which technologies to emphasize. Environmentalists may look mainly to "green" technologies to reduce dependence on fossil fuels. Coal industry executives may look to technology to make their product the preferred fuel in Asia's rapidly growing energy markets and the principal source of synthetic liquid fuels. But both would agree that technological progress is the key to raising living standards around the world while providing for 4 to 6 billion more people by 2100.

Technology has always played a vital role in economic and social development. Over the last 200 years technology has moved us from the farm to the factory to the Internet. Technology has done away with some environmental problems, e.g., urban horse manure, but has added others, e.g., urban smog. In the future, if we are to direct technological change so that solutions outpace problems, we must understand technology's history much better than we do today.

Technology and Global Change (Cambridge University Press, 1998, ISBN 0-521-59109-0, 452 pages, $30), by Arnulf Grübler of IIASA's Environmentally Compatible Energy Strategies (ECS) project, is the first book to give a comprehensive description of the causes and impacts of technological change over the last 200 years. The book

first defines the basic terminology, concepts, and models used to analyze technology and technological change. It then reviews 200 years' worth of technological change in agriculture, industry, and services and organizes history into a sequence of technology clusters—each with its distinctive environmental "footprint." Third, *Technology and Global Change* offers conclusions addressing the "paradox" of technology and the environment, and a postscript illustrating analytical next steps toward creating more successful models of technological change.

Technology Lifecycles: Success, Failure, Luck, and Perseverance

Any realistic history of social and technological innovation would consist mostly of failures. Many more ideas are proposed than ever succeed, and even those that succeed often turn out very differently from those first imagined.

Consider first a success, the bicycle. The bicycle is the most successful transport technology in history, with currently more than 100 million bicycles produced and sold each year, compared to fewer than 10 million cars. But today's bicycle is very different from its 19th century predecessors, for example the "Penny-farthing" design with its huge front wheel and tiny back wheel. The evolution of the bicycle over the years reflects, in part, interconnected developments in related technologies such as Dunlop pneumatic tires and the rear chain drive. But it also reflects social developments and changing expectations of both consumers and producers, each responding to the other. The Penny-farthing, for example, was originally marketed to "young men of means and nerve," and it took many unsuccessful design innovations and 20 years before the bicycle's design stabilized around what we have today: a safe and comfortable means of transportation that just about anyone can afford and ride easily.

Thus, even with a successful technology, the long road from introduction to widespread acceptance requires time, trial and error, important complementary technological developments, and consistent readjustments as producers react to changing consumer preferences and consumers react to changing alternatives. But it would be wrong to think of this as simply a journey from an initial "bad" design to an eventual "good" design. The initial design only got a chance to evolve because it appealed to a niche market ("young men of means and nerve") through which clever designers and entrepreneurs gained experience that they were able to turn into alternative designs and wider appeal.

In addition to the importance of niche markets, a second lesson from the bicycle's success is that changes in how consumers use a technology are as important as clever engineering if the technology is to be used widely and exploited to its full potential. As another example, take the case of electrification in factories, which involved 50 years of gradual organizational adjustments to make better and better use of the technology. Factories had previously been powered by steam, which, like its predecessor water, was a centralized source from which power was distributed to individual machine tools through systems of shafts and transmission belts. Initially, new electric motors simply replaced centralized steam engines, and power distribution remained unchanged. Then several centralized electric motors were used instead of just one, but productivity increases were still modest. The turnaround came only in the 1920s, when each machine was equipped with its own electric motor. This meant that machines could be located to optimize production rather than simplify power transmission, and that power was only used when it was needed. The result was an increase in energy efficiency by a factor of up to three. An analogy between this experience and current computerization has been suggested. Today, according to Nobel Laureate Robert Solow, " . we see the computer everywhere but in the productivity statistics." But perhaps the measurable impact of computers on productivity will depend on several decades of organizational adjustments comparable to those required in electrifying factories.

The bicycle and the electric motor represent two widespread successes. However, as noted above, most technologies end in failure. But we can learn lessons even from these. *Figure 1* shows some of the over 1000 patented smoke spark arresters, inventions intended to solve the

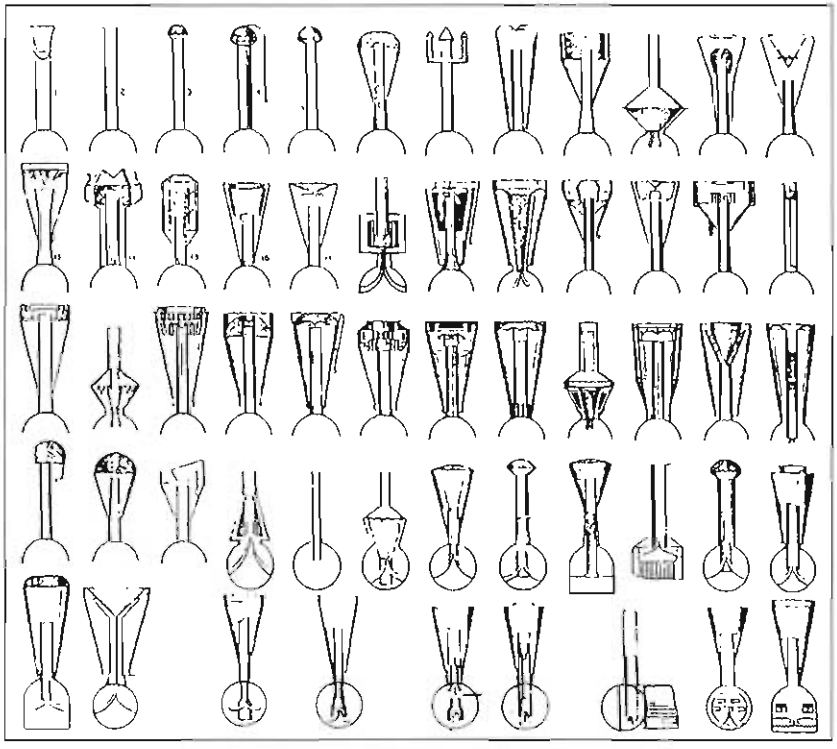


Figure 1: Technological variety in response to an environmental hazard. A few examples of the more than 1000 patented "smoke-spark arresters" for wood-burning steam locomotives in the USA. None of them was successful. Source: G. Basalla, 1988. The Evolution of Technology. *Cambridge University Press.*

problem of sparks from wood-burning steam locomotives regularly setting American forests ablaze. None of these designs ever enjoyed success. In the end, the problem of smoke sparks was solved not by any "add-on" technology in the form of a smoke spark arrester, but by a radical technological change—the replacement of steam by diesel and electric power—driven largely by other considerations. Thus, while clever designers and entrepreneurs able to exploit niche markets are the key to technological success, spillovers from other industries and sometimes sheer luck are important too. A confluence of developments in related technologies (e.g., cheap oil, refineries, pipelines, large diesel engines, and generators in the case of locomotives) is often a central part of ultimate success, and unforeseen developments, even in apparently unrelated technologies, can make a whole patent office worth of smoke spark arrester designs obsolete in short order.

Engineering skill, organizational skill, entrepreneurial skill, available niche markets, spillovers, time, and luck are thus all important to technological success. So is money. *Figure 2* shows the costs of photovoltaics in Yen per Watt installed capacity. Costs have fallen from 30,000 Yen in 1973 to 640 Yen per Watt 20 years later, an improvement by almost a factor of 50. But such progress has a price, as shown on the horizontal axis in *Figure 2*. Altogether more than 200 billion Yen in constant 1985 Yen (equivalent to about US$2.5 billion at present prices) have been spent to achieve that factor of 50 reduction in price. About 20 percent of the total was spent on R&D, which provides the essential basis for improving the technology. The other 80 percent went into the tangible investments in niche market applications required to gain experience and guide further R&D. Such investments are the essence of "learning by doing"; indeed, without them there is a risk of forgetting by *not* doing. But even after these investments and impressive cost reductions, far more money must still be invested before photovoltaics will be competitive enough to diffuse rapidly in mass markets.

Technology Clusters in History

No technology is an island. Automobiles, for example, depend on the oil industry to extract, refine, and deliver their fuel. They depend on roads, ferries, tunnels, and bridges. And they depend on economies that include garage mechanics, driving instructors, licensing agencies, traffic control, police and traffic courts, and many incentives for individuals to climb in their cars to go somewhere. These multiple contributors to the car's success did not all develop at once. But progress in each of these technologies facilitated and reinforced progress in the others in a sort of virtuous cycle, leading to impressive expansion of these interrelated technologies as a group.

Groups of technologies that advance and expand synergistically are an important and common feature of technological history. To help understand technology's role in global change, *Technology and Global Change* identifies four such groups, or technology clusters, that have driven technological progress over the past 200 years, plus a possible fifth technology cluster now emerging as we begin the new millennium. *Table 1* summarizes two such clusters in terms of key developments in different economic sectors, their geography of technological diffusion, and their global change impacts.

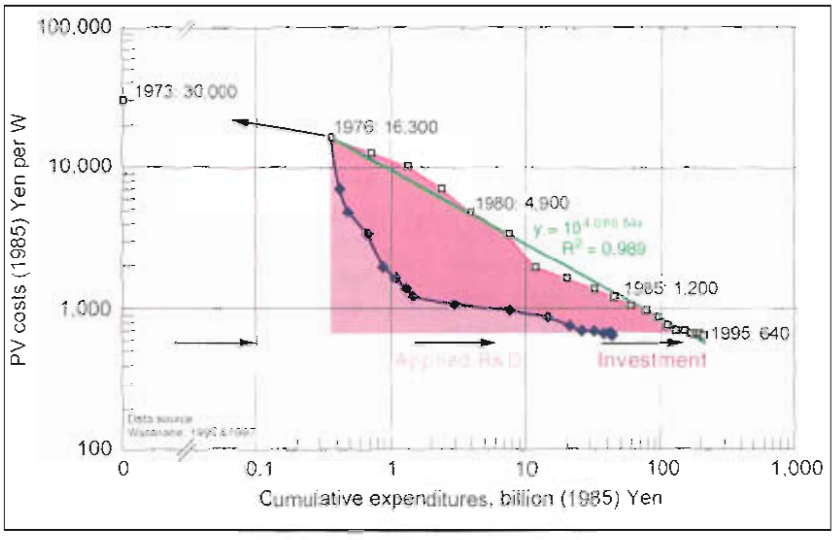


Figure 2: Costs of photovoltaics, in Yen, per Watt installed capacity. Data source: C. Watanabe, Tokyo Institute of Technology and IIASA.

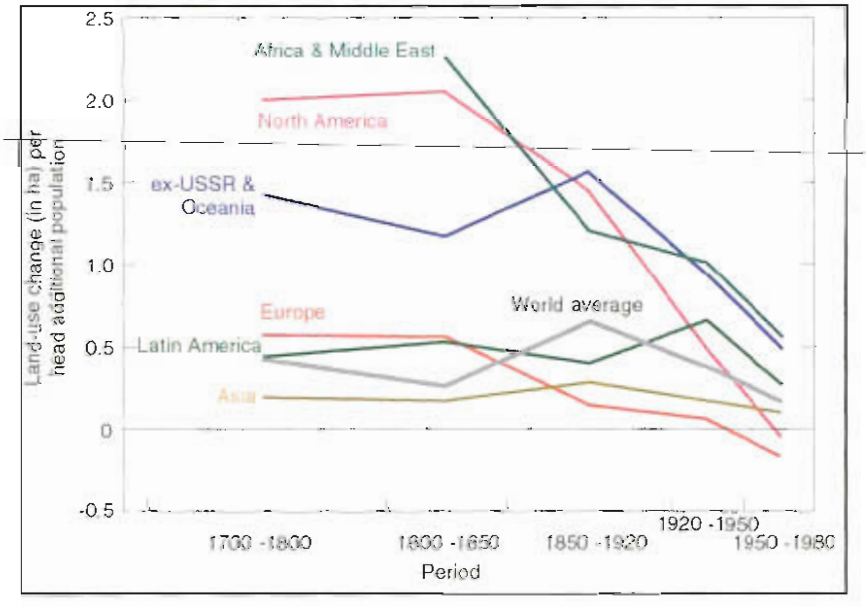


Figure 3: Land-use changes (in hectares) per head additional population. Average for six world regions and the world for five successive time periods since 1700.

Technology cluster of period		
	1850–1940	1920–2000
Agriculture	Mercantilistic Agriculture	Industrialization of agriculture
Industry	Heavy engineering	Mass production
Services	-	Mass consumption
Dominant energy and transport systems	Coal, railways	Oil, roads
Diffusion geography		
"Center"	Benelux, England, France, Germany, USA	OECD countries
"Catching up"	Other OECD countries	Eastern Europe, Russia
Illustrative direct/indirect global change impacts	Yield increases: reduced land-use changes ("center")	Yield increases: reconversion of agricultural land ("center")
	Agricultural trade ("export" of impacts to ROW)	Reduced land-use changes (ROW)
	Urbanization ("center")	Urbanization (ROW)
	Urban air pollution, coal smog	Acid rain ("center"), Urban smog (ROW) Ozone depletion Greenhouse gas emissions

Abbreviations: OECD, Organization for Economic Cooperation and Development; ROW, rest of world.

Table 1: Summary of the two important technology clusters of the 20th century and some of their global change impacts. Each cluster spans approximately a period of 50 years, with a 20-year period overlap with the preceding and successive clusters, respectively.

The Paradox of Technology and the Environment

Technology is both the source of and the remedy for environmental change. That is the paradox. The critical questions are, first, which aspect of technology—as source of or remedy for environmental change—currently has the upper hand and, second, how can we tilt the scales toward the latter?

Consider first some positive trends. *Figure 3* demonstrates how the amount of land needed to feed an additional person has changed through history. First, the figure shows that there are persistent differences among regions. History matters, and the future trends in a region depend on past trends—a phenomenon common in technological history and known as path dependency. Second, there has been a general decrease over time in all regions. In the 20th century in particular, increases in agricultural productivity through technology have become a truly global phenomenon. Everywhere less land must be converted to cropland to feed each additional person. Third, as shown on the far right side of the figure, the trends for Europe and North America have dropped below zero. Technology has increased agricultural productivity so much in these regions that cropland is being reconverted back to grassland and forest cover even as populations (and production) continue to grow. More people can be fed using less land. Technology as a remedy for environmental change has finally outpaced technology as a source of environmental change.

Recent trends in the use of several key metals—copper, lead, and zinc—offer a second example of good news. Because of technological progress, we use these metals increasingly efficiently and thus generate fewer waste emissions of each for each dollar of gross national product (GNP) that we produce. But such improvements could be offset if national GNP were to grow faster than efficiencies were to improve. The good news is that for the last few decades efficiency improvements have been at least as fast as economic growth, at least in the advanced industrialized countries that dominate global materials use. Absolute emissions are decreasing, despite still-growing populations and economies. Technology as a

remedy for environmental change is again beginning to outpace technology as a source of environmental change.

Unfortunately there are also many examples of ever-increasing output and environmental stress. Previously, we noted that new transport technologies solved the problem of urban horse manure. If each horse had been replaced by only one car, the car would be considered an environmentally friendly technology. What actually happened was of course very different. *Figure 4* shows how personal mobility in France has grown by a factor of 1000 over the last 200 years. With such spectacular growth in mobility, demand growth has overwhelmed any technological improvements to reduce emissions. In this case, technology as a source of environmental change has outpaced technology as a remedy.

Transportation and cars also illustrate the importance of *how* technologies are used, as well as *what* technologies are used. Since 1970, for example, specific fuel consumption for U.S. passenger cars has declined by 30 percent and total passenger-kilometers driven have increased only slightly. Nevertheless, total carbon emissions have increased by 20 percent. Why? The answer is that there are fewer and fewer people in any given car at any given time. The number of "empty seats" being driven around has increased by 20 percent. These changes have been sufficient to more than negate all the energy savings and carbon emission reductions that would have otherwise come from the improved fuel efficiency of U.S. cars.

Lightening Our Tread

Through technology, humanity has for 200 years increasingly liberated itself from the environment. The job is not yet complete. Billions of people continue to be excluded from the benefits of technology, and the next immediate task is to ensure their inclusion. But for the 21st century, the challenge is to progressively liberate the environment from adverse human interference. For this we will need more technology, not less. As the world's population grows to 10 billion or more, we cannot fully shield nature from human intervention, but technological change can relax our grip and lighten our tread on the natural world. To guide policies in this direction we will need better models of technological change than we have today. *Technology and Global Change* concludes with a summary of important methodological developments achieved at IIASA over the past two decades that open the way to a better understanding, and better models, of the interactions between technological and environmental change. Fortunately, we already possess extensive knowledge on patterns and characteristic rates of technological change. Improved models exist that enable a better theoretical understanding of the cumulative nature of technological change. In addition, even newer models are becoming available that no longer treat technological change as something external to the sorts of economic and social trends cited in the examples above. Instead, they incorporate such advances as an intrinsic factor.

Building upon these resources, and upon others not yet implemented or even anticipated, researchers and model developers can contribute significantly to ensuring greater synergy between improved human welfare and a healthy natural environment. ■

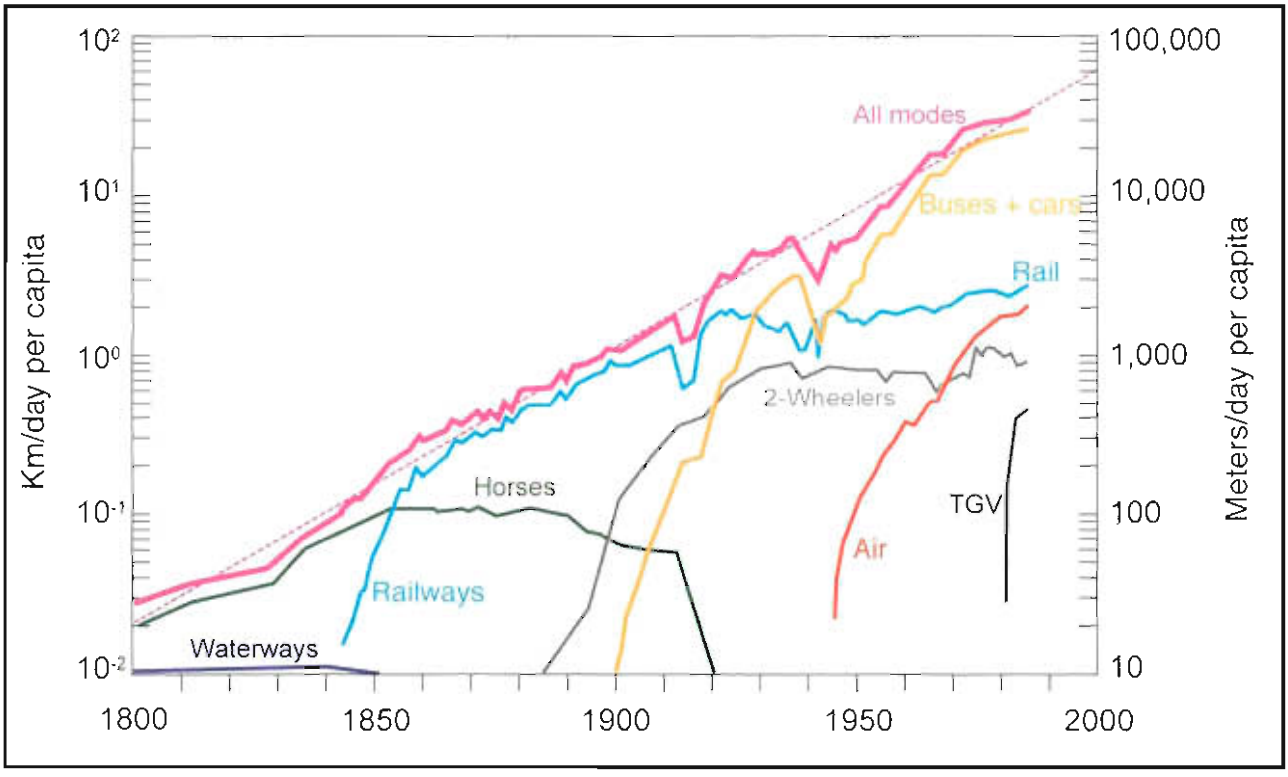


Figure 4: Growth in personal mobility, (km travelled per day per person) in France over the past 200 years.

Inside IIASA

IIASA COUNCIL RE-APPOINTS MACDONALD

The IIASA Council has reappointed **Gordon MacDonald** to serve an additional 3-year term as director of IIASA.

Arne Jernelöv, the Council representative from the Swedish National Member Organization (NMO), was appointed as chair of the IIASA Council.

The U.S. NMO has chosen **Gordon Wolman** of Johns Hopkins University as its Council member. Wolman takes over for John Ahearne, who was named an IIASA honorary scholar.

ACHIEVEMENTS

In August, IIASA's Adaptive Dynamics Network project member **Karl Sigmund** presented a plenary lecture at the International Congress of Mathematicians (Berlin, Germany). The highly select plenary lectures at this quadrennial event reflect the major developments, problems, and trends in mathematics. Sigmund is the first Austrian mathematician to be granted the honor of a plenary lecture for several decades, and his presentation on "The Population Dynamics of Conflict and Cooperation" was the first such lecture to report on the burgeoning field of biomathematics. Sigmund's contribution received extensive press coverage.

MEETINGS

Implementation Workshop for the SIBERIA CEO/INCO/ESA Project
August 9 - 11
Contact:
Sten Nilsson,
nilsson@iiasa.ac.at

Fourth DAS Workshop on Multiple Criteria Support in Network Centric Organizations and One-day Tutorial on Foundations of Decision Support Methodology
Istanbul, Turkey
September 1 - 4
Contact:
Pekka Korhonen,
korhonen@iiasa.ac.at

EU Project Meeting "Potential Use of Renewable Sources of Energy in Asia and their Cost-effectiveness in Air Pollution Abatement"
September 9 – 11
Contact:
Markus Amann,
amann@iiasa.ac.at

IIASA Workshop on Advances in Modeling: Paradigms, Methods and Applications
September 21 - 23
Contact:
Marek Makowski,
amap@iiasa.ac.at

CSM'98: 12th JISR-IIASA Workshop on Methodologies and Tools for Complex System Modeling and Integrated Policy Assessment
September 24 - 26
Contact:
Marek Makowski,
csm98@iiasa.ac.at

Evolutionary Conservation Biology: The Genetics of Rarity
November 29 - December 1
Contact:
Ulf Dieckmann,
dieckman@iiasa.ac.at

The Time Pattern of Cost and Benefits of EU Accession
December 3 - 5
Contact:
Janos Gacs,
gacs@iiasa.ac.at

Issues in Decision Analysis and Support
December 9 - 12
Contact:
Pekka Korhonen,
korhonen@iiasa.ac.at

Evolutionary Conservation Biology: Adaptive Responses to Environmental Threats - from Individuals to Ecosystems
December 13 - 15
Contact:
Ulf Dieckman,
dieckman@iiasa.ac.at

NEW STAFF

Michael Gluck has joined the Forestry project as a systems analyst addressing questions of forest sustainability through the use of geographic information systems. Before coming to IIASA, Gluck was a planning analyst with the Ontario Ministry of Natural Resources, where he was responsible for developing tools to support strategic land-use planning, and for the development and implementation of methodologies for assessing landscape patterns.

Michael Gluck

Kazuo Inaba is spending a year with IIASA's project on Economic Transition and Integration (ETI) as a guest research scholar, carrying out econometric research on Japanese corporate investments

and technology transfer abroad and, through this, assisting ETI's research on integration of transition countries to the world economy. Inaba is a professor at the Faculty of Economics, Ritsumeikan University in Kyoto, where he is working in the field of international economics, especially modeling Japan's overseas direct investment.

Kazuo Inaba

Ger Klaassen has returned to IIASA to work with the Environmentally Compatible Energy Strategies project on global and regional energy development, environmental compatibility, and technology dynamics. Previously, from 1990 to 1995, he worked at IIASA in the Transboundary Air Pollution project on the costs of controlling ammonia emissions and the use of economic instruments. From 1996 to mid-1998 he served in the Directorate General for the Environment of the European Commission in Brussels as the expert responsible for the economic aspects of climate, energy, and air quality policies.

Ger Klaassen

IIASA SOCIETY FORMALIZES STATUS

The IIASA Society, an organization that brings together IIASA research alumni, has decided to change its status and become a legally recognized association under Austrian law. The new status marks an important milestone for the Society. Although efforts were made in 1989 to reach out to IIASA alumni and help them maintain contact with the Institute, it was IIASA alumnus Nathan Keyfitz who really brought life to the IIASA Society. In response to a letter Nathan sent out in 1993, more than 400 alumni returned registration forms indicating that they would like to become members of the Society.

A one-year hiatus followed, but Nathan, back in the United States, and still the spirit behind this project, prepared another letter that was mailed to 2000 alumni. This marked the start of an alumni association that now communicates mostly via the Internet

Under its new legal status, the Society's activities, finances, and projects are now independent of IIASA; however, the Institute still provides office, computer and modest financial support. Temporary officers of the Society are:

President: Nathan Keyfitz

Vice Presidents: Erna Wodak, Tom Schelling

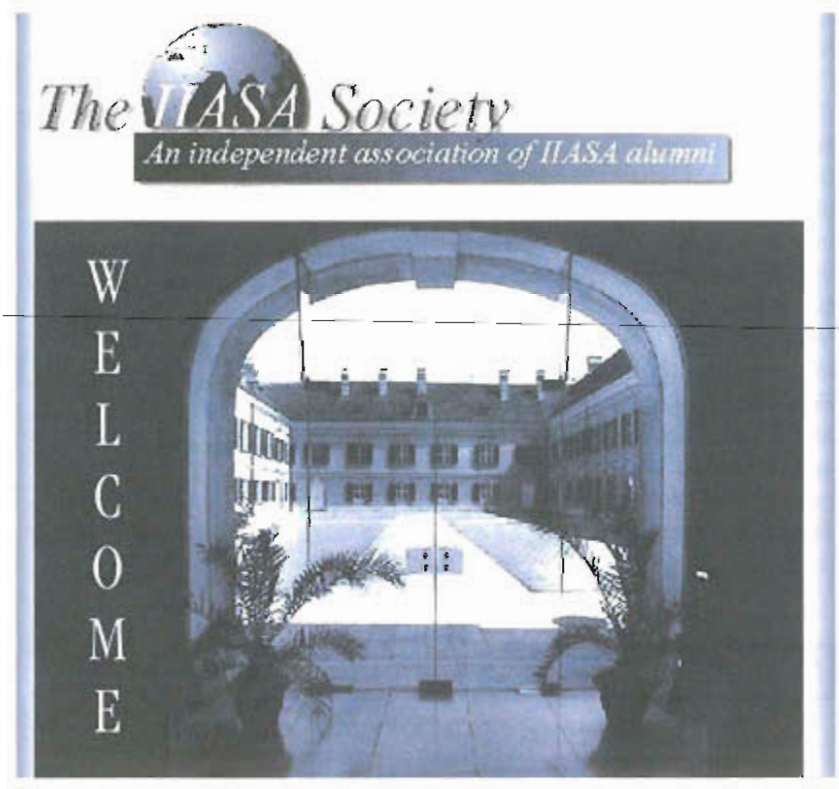
Treasurer: Hans-Holger Rogner

Secretary: Linda Kneucker

Alternative Secretary: Shari Jandl

Elections will be held electronically for officers, who will serve for two years.

A hard copy mailing was sent to all alumni who had not supplied IIASA with an e-mail address. For more information, and to register online, visit the IIASA Society home page at: www.iiasa.ac.at/IIASA_Society, or contact Linda Kneucker at *kneucker@iiasa.ac.at*.



The IIASA Society home page on the World Wide Web: www.iiasa.ac.at/IIASA_Society.

Three Receive YSSP Scholarships

IIASA's Young Scientists Summer Program (YSSP), which enables graduate and post graduate students to gain hands-on research experience during a three-month stay at the Institute, each year awards one or more Peccei Scholarships and one Mikhalevich scholarship to participants whose work shows outstanding promise. These scholarships allow the recipients to return to IIASA for three additional months of research.

This year's recipients of the Peccei Scholarship are **Anton Dobronogov**, of the University of Kiev, and Margaret Taylor of Carnegie Mellon University. Dobronogov's research, performed with the Social Security Reform project, involved modeling the Ukrainian pension system. **Margaret Taylor** earned the scholarship for her research on innovation in environmental technology, working with the project on Environmentally Compatible Energy Strategies.

Gebhard Banko of the University of Agricultural Sciences, Vienna, received the Mikhalevich Scholarship, which rewards methodologically oriented work. Under the guidance of the project on Sustainable Boreal Forest Resources (FOR), Banko researched methods to assess the accuracy of maps from remote sensing data. In addition, IIASA awarded an honorable mention citation to **Gidske Andersen** of the University of Bergen at Solheimsviken, Norway, for her work in the FOR project on developing methods to classify and estimate forest variables in high-resolution satellite data.

IIASA project leaders submitted 11 nominations to the evaluation committee, which consists of the dean and vice-dean of the YSSP and the IIASA director. The committee reviewed 11 nominations and received comments from outside experts before selecting the winners.

IIASA established the scholarships in memory of two prominent IIASA alumni: Dr. Aurelio Peccei, a founder of IIASA and former president of the Club of Rome; and Academician Vladimir S. Mikhalevich, former Soviet (subsequently, Ukrainian) NMO representative to IIASA and chairman of the IIASA Council, as well as member of the Ukrainian and Russian Academies of Sciences and professor at Kiev University.

Research Grants

Project	Sponsor	Study
Adaptive Dynamics Network	European Science Foundation	Two workshops on evolutionary conservation biology
Environmentally Compatible Energy Strategies	Keio University, Japan	Software support for technology inventory/ updating energy and environment data
	Central Research Institute of Electric Power Industry (CRIEPI)	Global energy supply and demand and their environmental effects
Forestry	U.S. National Science Foundation	MEDEA Russian boreal forest monograph
	European Commission DG XII	SAR Imaging for Boreal Ecology and Radar Interferometry Applications (SIBERIA)
Processes of International Negotiations	The Swedish Council for Planning and Coordination of Research (FRN)	Processes of International Negotiations
Population	Hubert H. Humphrey Institute of Public Affairs, University of Minnesota	Rethinking population projections
Risk, Modeling and Policy	European Commission DG XII-G3	Two workshops on global change and catastrophic risk management
	Cook Street Holdings Inc.	Modeling of using financial markets to securitize catastrophic risk
Transboundary Air Pollution	Central Research Institute of Electric Power Industry (CRIEPI)	A comprehensive assessment of large-scale environmental problems in East Asia
	European Commission DG XI	Economic evaluation of a directive on national emission ceilings for certain atmospheric pollutants
	Swiss Agency for the Environment, Forests and Landscape	Further scenario calculations for the Second NO_X Protocol

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	Global Energy Perspectives, Paperback £ 16.95 N. Nakicenovic, A. Grübler, A. McDonald (eds)	0521645697	£
	Technology and Global Change, Hardback £ 30.00 Arnulf Grübler	0521591090	£

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The Ministry of Environment and Waters

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The Finnish Committee for IIASA

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The Association for the Advancement of IIASA

Hungary
The Hungarian Committee for Applied Systems Analysis

Japan
The Japan Committee for IIASA

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Norway
The Research Council of Norway

Poland
The Polish Academy of Sciences

Russian Federation
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