EPRI

Electricity Technology Roadmap

POWERING PROGRESS

1999 SUMMARY AND SYNTHESIS

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POWERING PROGRESS

CI-112677-V1

July 1999

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Executive Overview

"Where there is no vision, the people perish"

Proverbs 29:18

The Electricity Technology Roadmap Initiative is an ongoing collaborative exploration of the opportunities and threats for electricity-based innovation over the next 25 years and beyond. Thus far, over 150 organizations have participated with EPRI and its members in shaping a comprehensive vision of the opportunities to increase electricity's value to society. This vision is being translated into a set of technology development destinations and the R&D pathways to reach these destinations. EPRI is leading this ongoing roadmapping effort as an investment in the future, and as guidance for strengthening the value of public and private R&D investment.

The Electricity Technology Roadmap Initiative explores a period of immense technological and institutional change in the electricity enterprise and in the society it serves. The choices made in such periods of change can have profound consequences on whether future opportunities are opened or foreclosed, and whether threats are eliminated or realized. This heightened need for foresight motivates the Roadmap Initiative.

The first year of the Roadmap's development is synthesized in this report. It is supplemented by topical area reports on electricity supply, electricity delivery, electricity and economic growth, the environment, and global sustainable development. Key conclusions and recommendations reached thus far follow:

1 **Electricity-based innovation is central to productivity growth. As such, it lies at the heart of sustained growth in the global economy, a "long boom" of unprecedented expansion and social transformation projected through 2020 and beyond.**

- The precision and flexibility of electricity has powered the industrialized world from the era of smokestacks into the era of knowledge-based services shaping the 21st century.
- Electricity enables the global real-time network for communication, finance, and trade. This network is becoming not only the backbone of the knowledge-based global economy, but also a highway for developing nations to accelerate their way out of poverty.
- Technology innovation has emerged as the primary driver for economic growth. The importance of innovation—much of it from electricity-based productivity improvements—is expected to continue to grow in the future.
- Accelerated productivity growth is essential to resolving the widening pension and health-care deficits of an aging population. The alternative is a spiraling economic burden for a shrinking work force.
- Electricity is expected to play a profound role in helping society seize the opportunities and manage the threats emerging in the new century. These will be shaped by:
    - An expanding and interconnected global economy
    - The deregulation of historically controlled markets
    - The revolution in information technology
    - The revolution in the way energy and electricity are used and valued
    - The global demographic explosion
    - A series of escalating environmental challenges related to population growth

2 As key to both energy efficiency and energy diversity, electricity will increasingly shoulder society's burden for energy-related environmental control and cleanup.

- The pace and scope of technological change in the electricity industry is greater today than at any time since the dawn of commercial electrification. The change process is likely to accelerate as:
  - The opportunities for efficient conversion to electricity move closer and closer to the customer
  - Power electronics usher in a new age of precision delivery of power
  - Electrotechnologies boost industrial and service sector productivity to new heights with greater energy efficiency and reduced environmental impact
  - Information technology redefines the boundaries and relationships between producers and customers, creating near-frictionless markets
- Electricity is the equal opportunity medium that brings diverse energy sources to market. It is the key to diversifying transportation fuels beyond petroleum, with enormous strategic advantages for global security.
- The Roadmap envisions the ability to cut global energy intensity, while accelerating the decarbonization of the global energy system through electrification.

3 A new mega-infrastructure is emerging from the convergence of electricity and communications. This will open the gateway to new "intellectric" services that place unprecedented levels of individualized comfort, convenience, speed, efficiency, and adaptive intelligence at the customer's fingertips.

- The digital microprocessor is penetrating every aspect of the economy and society, thereby increasing the efficiency and precision advantages of electricity to the level, literally, of individual electrons. This is shifting the energy business dynamic from the supply of commodity-value electricity to the delivery of value-added services through intelligent, customer-managed service networks.

- These customer-managed, energy/information networks are expected to open new lines of business, provide a vehicle for increasing energy efficiency, and establish an important conduit for introducing innovative technologies upstream and downstream of the meter.

- Failure to aggressively pursue these network capabilities carries large opportunity costs, including higher infrastructure costs as utility service integration is slowed or stopped, as well as constraints on the development of productivity-enhancing technology.

- In this more competitive, energy-converging world, energy users are unlikely to have any special affinity for either the electron or the hydrocarbon molecule; rather, they will emphasize the value of the services that energy enables. As a result, providers of energy commodities, as well as owners of delivery grids, will need to more actively engage in the growth of end-use value in order to sustain their businesses.

4 Continued realization of these opportunities, however, will be paced by the ability of the electricity delivery system to both meet the increasingly diversified requirements of a competitive marketplace, and maintain power reliability and power quality as transactional volume and open-access complexity increase.

- The current power delivery grid was not designed to meet these emerging demands.
- Power-electronic control and wide-area management technologies that are available or under development can alleviate the growing potential for outages, power disturbances, and operational constraints in an open-access electricity grid.
- Proper incentives, including elimination of institutional uncertainties, are urgently needed to ensure timely and sufficient investment in the development and deployment of these innovations.
- The evolution of ever smaller and lower-cost distributed generation technology is creating commercial alternatives to centralized power generation and its delivery grid for meeting the escalating marketplace demands in energy services and quality.

5 The Roadmap targets the "2% solution" as the most plausible pathway to global sustainability. Robust electricity-based technological innovation is an essential basis for this solution pathway.

- Creating a sustainable future will require the "2% solution"—that is, global improvements in a number of areas, including economic productivity, energy efficiency, emissions reduction, agricultural yield, and water consumption, at a rate of 2% or better each year over at least the next half century.

- This 2% solution recognizes that only growing economies are able to provide the resources needed to solve environmental problems and meet the quality of life aspirations of people today and in future generations. The fact that world population may reach 10 billion people by 2050, with 90% of the growth occurring in today's poorest nations, heightens the urgency of this realization.

- There are no insurmountable barriers to the energy resources needed to fuel the 2% solution, provided the commitment is made to the essential technological progress that is needed across the portfolio of resources—fossil, nuclear, renewables—and to the global dissemination of the results.

- Electrification is an essential vehicle for productivity improvement and sustainable development. In particular, it can help developing nations leapfrog over the earlier and relatively inefficient development pathways followed by today's more affluent industrialized nations in order to enjoy an improved quality of life with much higher resource efficiency.

- To keep pace with the world's rapidly growing population and provide a foundation for the 2% solution, electrification must reach an additional 100 million people per year for at least the next 50 years, more than twice the current rate of expansion. Moreover, a universal foundation of at least 1000 kWh per capita per year will be needed to achieve acceptable levels of literacy, health, and security, and to enable sustainable global economic growth.

6 **A strategic science and technology initiative is urgently needed to address climate change concerns within the context of the 2% sustainability solution. It will be essential to avoid conflicting, short-term responses that tend to "lock in" existing technology, constrain efficient economic development, and slow the technology innovation needed for long-term sustainability.**

- Global greenhouse warming is the contingent risk on which the global energy future hinges. Fundamental research into the science and economics of this risk must be accelerated to provide the necessary guiding knowledge.

- This climate change concern is a long-term issue requiring a truly sustainable solution. Allowing both time and geographic flexibility for emission reduction through technology advancement would dramatically reduce the cost of stabilizing atmospheric concentrations of greenhouse gases and the threat to sustainable economic development.

- Providing the electricity needs of the world's rapidly growing population will require adding the equivalent capacity of a 1000 MW power plant about every two days for the next 50 years. By the year 2050, the resulting 10,000 GW of aggregate global capacity will generate as much as 60 trillion kWh annually, representing about two-thirds of global primary energy consumption.

- Within this context of growth, it is not feasible to stabilize atmospheric CO_2 concentrations at acceptable levels without substantial improvements in efficiency and the expanded use of carbon-free nuclear and renewable energy. Fundamental technology breakthroughs for these energy sources will be needed to allow global deployment of nonfossil energy on the scale required.

- Therefore, a critical priority is the development and deployment of an advanced portfolio of generating technology options—fossil, nuclear, renewables—that reflects the diverse resource, environmental, and economic realities of the new century, while enhancing efficiency throughout the entire energy supply chain.

7 A significant, sustained pattern of under-investment in both energy R&D and energy-related infrastructure threatens the world's long-term economic prosperity, environmental health, and security.

- Public expenditures on energy R&D have declined by a third over the last 20 years, and less than 10% of that funding goes to energy-efficiency improvements. Under-investment in energy technology R&D is detrimental to both long-term energy security and global sustainability. Further, it could foreclose technology options that the global community will need to systematically address the environmental impacts of energy.

- U.S. public investment in all the basics of innovation—education, R&D, and infrastructure—has fallen from around 25% of non-defense expenditures in 1965 to 12% in 1995. The economic dangers of this under-investment will be greatly magnified by global competition, a shrinking workforce, and the needs of an aging population in the new century.

- This under-investment trend is particularly evident in technology-intensive infrastructures, notably electricity. The historic debate about whether the public or private sector should pay, compounded by preoccupation with industry restructuring, is retarding investment in innovation and its R&D engine. An effective response will require renewed public/private collaboration that recognizes infrastructure excellence as a prerequisite for productivity growth, economic prosperity, and environmental health.

8 Complacency based on current U.S. leadership in R&D and advanced education could be disastrous. Rapidly growing international capabilities are shaping new realities, which need to be addressed in tax, regulatory, education, and immigration policies.

- The robust short-term performance of the U.S. economy today encourages complacency about innovation in both the public and private sectors. A strong case can be made, however, that today's innovative achievements are a legacy of historic assets that are not being renewed.

- Sustained innovation is the key to maintaining prosperity. High wages cannot be justified unless new products, services, and processes are continually created. Electricity is the essential platform for innovation, but the value realized will increasingly depend upon superior technological strength achieved through a vigorous, ongoing commitment to R&D, education, and the other fundamentals of productivity growth.

- The U.S. is in a stronger position than any other nation to lead the essential balancing of global economic and environmental imperatives, but that window of opportunity will diminish under rising global demographic pressures. The U.S. and the other most affluent industrialized nations are a shrinking minority of the world's population.

- Globalization is also leveling the innovation playing field and collapsing the margins of technological leadership. Roadmap participants question the preparedness of the U.S. for success in a world with a much broader capacity to innovate.

- The crux of the challenge is to rebuild the broad national consensus that created the assets for innovation on which the nation is now drawing. That consensus has dissolved since the end of the Cold War and must be urgently renewed if prosperity is to be confidently maintained.

9 As shown in the table below, Roadmap participants recommend an increase of nearly $5 billion/year in U.S. electricity technology-related R&D to effectively reach four priority destinations. Participants also recommended a reevaluation of existing programs and, where appropriate, a redirection of funding to the high-value opportunities identified by the Roadmap.

Estimated 10-Year Funding Requirements for the Roadmap Research Program ($ million/yr)

Destination	Current Funding	Additional Funding Needs	Total Funding
Strengthening the Power Delivery Infrastructure	400	600	1,000
Enabling Customer-Managed Service Networks	400	500	900
Boosting Economic Productivity and Prosperity	700	1,500	2,200
Resolving the Energy/Carbon Conflict	1,600	2,000	3,600
Total	**3,100**	**4,600**	**7,700**

In addition to the funding recommendations identified in this table, a substantial global investment will be needed to reach the Global Sustainability Destination. Roadmap participants have not yet attempted to quantify this requirement, but anticipate it will be much larger than that identified for the other destinations and will require a coordinated international commitment over many years.

1 Introduction to the Electricity Roadmap

...An Overview and Vision

This document summarizes progress on a collaborative exploration spearheaded by EPRI—the Electricity Technology Roadmap Initiative. With over 150 participating electricity stakeholder organizations, the Roadmap Initiative seeks to develop a comprehensive vision of opportunities for electricity-related innovation to benefit society and business. The Roadmap also translates that vision into a set of technology development destinations and ultimately the needed R&D pathways. EPRI is leading the Roadmap effort—intended to be an ongoing activity with wide participation—to guide broad-based public and private R&D investment in the electricity infrastructure and the innovations it makes possible.

The Future of Electric Power

The role of electric power has grown steadily in both scope and importance over the past century. Developments in key technologies such as electric lighting, motors, computers, and telecommunications have continuously reshaped American life, as well as the productivity of its commercial and industrial foundation. These technology advances have steadily extended the precision and efficiency attributes of electricity. As a result, electricity has gained a progressively larger share of total energy use, even as the energy intensity of the U.S. economy (energy per dollar of GDP) has declined. Electricity accounted for 25% of all energy used in 1970 and now accounts for nearly 40% of the total in the U.S. and in other countries with similar levels of economic development. The electricity system has emerged at century's end as the most critical infrastructure, in the sense that it enables all other infrastructures. In the coming decades, electricity's share of total energy is expected

Continuous technical innovation is key to sustained economic growth and environmental protection.

to continue to grow, as more efficient and intelligent processes are introduced into industry, business, homes, and transportation.

Electricity-based innovation—ranging from plasmas to microprocessors—is essential for enabling sustained economic growth in the 21st century.

The Roadmap Initiative

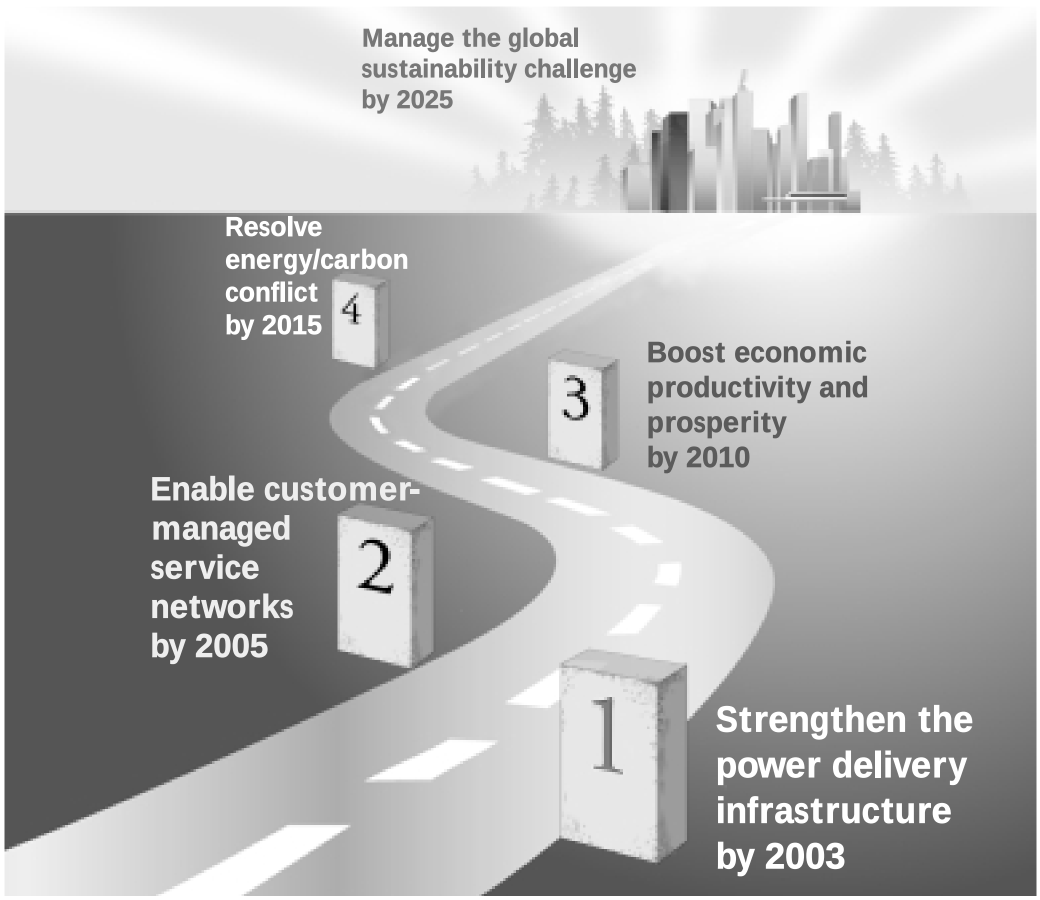
The window of opportunity offered by the institutional restructuring—or liberalization—of the electricity enterprise is a primary motivator for this Roadmap Initiative. The potential of restructuring goes far beyond the marginal cost savings from deregulation and the boundaries of the current industry, to the ways in which electricity can create value. EPRI began this Roadmap initiative to provide a structured means for a large, diverse group of stakeholders and technical experts to explore this potential in terms of new opportunities for electricity-based innovation to serve society.

The initial phase of this Roadmap exploration has identified a set of interdependent goals, or "destinations." These reflect the convergence of opportunities for a more prosperous, stable, and sustainable world, with the technological capabilities for their achievement. These five principal Roadmap destinations are:

- **Strengthening the power delivery infrastructure** by increasing its ability to meet the demands of competition, and strengthening it against natural disasters and man-made threats
- **Enabling customer-managed service networks** that exploit the value of the electron to provide interactive, integrated energy- and communication-based services
- **Boosting economic productivity and prosperity** by fostering the development of innovative electrotechnologies that enable the digital economy
- **Resolving the energy/carbon conflict** by most efficiently and economically addressing the technical challenge of controlling greenhouse gas emissions

• **Managing the global sustainability challenge** by meeting the needs of a growing world population for clean, efficient energy and the quality of life opportunities that electricity makes possible

The Roadmap destinations reflect the most important goals for the electricity and energy-related industries in the 21st century.



Roadmap participants identified knowledge and capability gaps that must be bridged to reach these destinations. These gaps pose key R&D, investment, and policy challenges that are now being examined to create and implement a comprehensive R&D plan. Although derived from consideration of a broad set of largely independent issues and challenges, several threads of logic link the destinations. Further, each destination builds on those preceding. Together, they create a unified picture of critical goals and challenges for the electricity and energy-related industries in the 21st century. Above all, these initial destinations represent only a glimpse of the opportunities in the "future of the future," and serve as a stimulating invitation to extend this vision. They are summarized here and elaborated in Chapters 2–6.

Power Delivery Infrastructure Challenge

The most immediate issue pacing the progress envisioned by the Roadmap is the vulnerability of the power delivery infrastructure, in terms of meeting the growing demands on electricity reliability. The existing radial, electromechanically controlled grid needs to be transformed into an electronically controlled, smart electricity network in order to handle the escalating demands of competitive markets in terms of scale, transactional complexity, and power quality.

The electricity infrastructure now underpins and integrates the entire U.S. economy. This pervasive dependence on electricity means that failures can easily propagate throughout the economy, multiplying the associated impacts. These reliability and power quality limitations already cost the U.S. economy more than $30 billion each year.

The upgraded system is not a luxury, nor even an option for the future. Rather, it is an imperative to build productivity and ensure global competitiveness in the $8+ trillion U.S. economy. The technology platforms needed to meet this power delivery system challenge include:

- Wide-area power flow control and advanced power electronic devices to facilitate the increasingly complex utilization of the transmission grid
- Superconducting transmission to increase grid-carrying capacity and efficiency
- Integration of distributed resources to increase the capabilities of power distribution systems
- DC microgrid capabilities that efficiently link digital end-use devices with local distributed resources and the transmission grid
- Grid-level power storage capabilities

Innovative technology is rapidly creating options that will allow all classes of customers with critical needs to bypass the grid. As a result, if the grid doesn't meet the growing performance challenge, its value could be steadily diminished to a provider of last resort.

Customer-Managed Service Networks

The electricity industry is expanding from its traditional dimensions to include energy services, power marketing, and information technology-based services and products—all designed to provide greater customer value. Roadmap participants expect this expansion to continue as the digital microprocessor permeates every aspect of the economy, and the power industry and its customers invest in advanced smart metering systems to exploit this value. Further, significant new business growth opportunities could be created by taking the next step: the transformation of the traditional power supply network into a truly customer-managed service network. When electrons are integrated with real-time information, customers can build customized services that are tailored to their particular needs. This transformed network can enable a flood of new intelligent electron services, or "intellectrics," that could place new levels of comfort, convenience, speed, efficiency, and adaptive intelligence at the customer's fingertips. A refrigerator linked to the Internet, for example, could negotiate for its energy requirements, call in for repairs, and even shop for food and beverages. In this new digital world, real-time information and the technology to exploit it are the key assets.

The transformed network will enable energy service providers to evolve into organizations that offer universal customer access to:

- Complete market information for making service choices
- Premium power, free of harmonics and distortion
- The lowest polluting energy available
- Overall energy efficiencies at least twice of those today
- Lower power prices

A key factor facilitating the customer-managed, digital world will be the growing convergence of the electricity and gas grids. In this world, distributed electricity generation could be placed almost anywhere on the grid, all the way down to and including the residential customer's premises, with microprocessors used at any of these points of potential generation in order to arbitrage the value and price of bulk electricity and gas to the customer's advantage.

Technology advances needed to support the development of real-time, interactive customer-managed service networks include:

- Modular electronic metering and the standards enabling universal customer access
- Advanced control and communications networks that enable broad-band communications capabilities
- Integrated underground service corridors for network infrastructure, including electricity, communications, gas, etc.

Economic Productivity and Prosperity

In a larger sense, the new mega-infrastructure of electricity and communications can act as a conduit for accelerating the introduction of electricity-based innovation into the economy, and for linking industrial processes in new and increasingly efficient ways. This will be essential for boosting productivity growth and enhancing competitiveness in key industries. In the fiercely competitive global economy of the next century, the U.S. will have to rely increasingly upon superior innovation for competitive advantage and economic prosperity. Historically, the nation's commitment to R&D and education has made innovation a differentiating strength for the United States. Today, that commitment is lagging.

To address the need for innovation, the Roadmap identifies a set of "technology platforms" that are common to multiple innovative applications. These platforms, which will help boost productivity in every sector of the economy, include:

- Efficient electrotechnologies for application in the process, manufacturing, and service sectors

• Advanced materials, sensors, and controls, including “smart” systems that can automatically adapt in real time to changing needs and conditions

• Microminiaturization of devices, processes, test systems, etc.

• Advances in information processing and modeling to enable increasingly complex interactive service networks

These enabling platforms for electricity-based innovation could make possible some major stretch goals for the U.S. economy, including:

• Doubling the growth rate of total factor productivity

• Cutting energy intensity in half

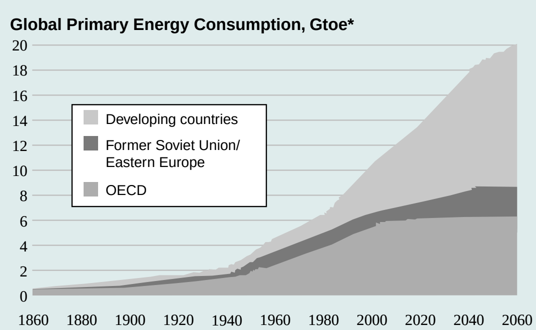
• Eliminating most waste streams

The results could add at least a trillion dollars a year to the U.S. GDP.

Energy/Carbon Challenge

An innovative, more productive economy is key to the two remaining Roadmap destinations. The first of these is the need to resolve the energy/carbon challenge, by meeting the rapidly growing global requirements for energy while preserving the environment. This will require an energy portfolio strategy that facilitates increasing use of noncarbon energy sources.

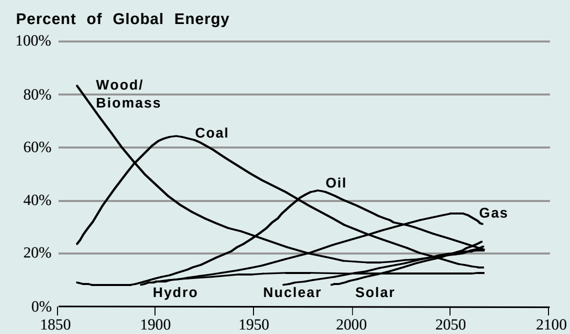
Most of the growth in primary energy consumption will come from developing countries.



*Gigatonnes of oil equivalent
Source: World Energy Council, World Bank

It would also accelerate the historic trend of gradual decarbonization of the global energy system, even as total energy demands have grown. Historically, decarbonization has been the result of industrial societies exploiting the convenience and efficiency of less carbon-intensive fuels. Thus, the progressive substitution of coal for wood, oil for coal, and in recent years, gas for oil. By 2050, the World Energy Council envisions the global energy mix to be made up of at least seven different sources, none of which is expected to have more than a 30% share of the market. Such a portfolio, with its balance and flexibility, reduces concerns over the availability of primary resources to meet the demands of continued growth. This provides a source of strength in meeting the uncertainties of the future. Only electricity can make this diverse supply portfolio possible while concurrently meeting global energy and environmental demands.

There will be less dominance and more diversity in world primary energy sources.



Source: WEC

Ultimately, the energy portfolio strategy is expected to result in an electricity/hydrogen energy system capable of providing globally abundant, clean, low-cost energy. This goal is feasible, but requires urgent global deployment of coal refinery technology now, as well as fundamental technical breakthroughs in nuclear and renewable energy technologies. The Roadmap calls for an immediate, accelerated global initiative to create this sustainable energy portfolio. This recommendation is driven by the recognition that the current power generation technology platforms—fossil, nuclear, and renewable—simply cannot be extrapolated to meet global needs either economically or environmentally.

Examples of potential breakthrough goals include:

- Transforming the energy and resource recovery efficiency of clean coal technology while making coal-based generation competitive with natural-gas-fired, combined-cycle generation
- Achieving a five-fold improvement in the cost, performance, and reliability parameters of solar photovoltaic power
- Developing advanced nuclear power generation with high fuel utilization and high efficiency (e.g., >50% in gas-cooled designs). This must be coupled with sufficient engineer-

ing advances in safety, waste handling, and proliferation control capabilities to ensure confident public support for the nuclear option

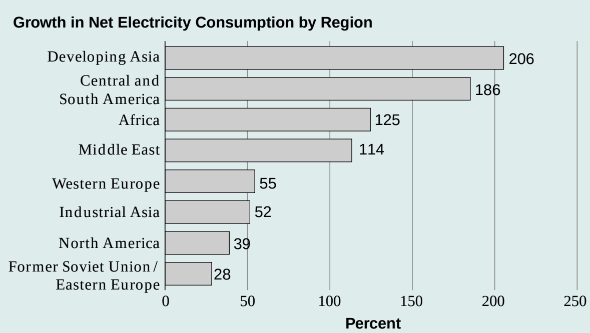
- Achieving large-scale, economic carbon sequestration to preserve fossil-fuel options during the transition to a more diversified energy future
- Broadening the array of available energy sources for distributed applications, both stationary and mobile
- Continuously improving end-use energy efficiency through electrotechnology advancements

Since no single power generation option can meet the needs of a diverse world, and since advances may occur in completely new fields yet to be developed, the Roadmap participants recommend a balanced portfolio approach to generation R&D that ensures the resource diversity needed for sustained global economic growth and environmental protection. Research is urgently needed to resolve these high-priority issues that are limiting fossil, nuclear, and renewable energy, while encouraging advances in basic sciences that may lead to new breakthroughs in power generation and utilization.

Global Sustainability Challenge

Global population may reach 10 billion people by 2050, with 90% of the growth occurring in today's poorest countries. Meeting the economic aspirations of people trying to lift themselves out of poverty, while still protecting the earth, will be a major challenge. It will require a rapid and sustained pace of technological innovation to stay ahead of the social and environmental problems associated with large-scale growth. Failure to meet the challenge could leave as many as 5 billion people without access to

Projected change in net electricity consumption by region, 1996–2020.



Source: Energy Information Administration/International Energy Outlook 1999 efficient energy or economic opportunity and trapped in a marginal existence—each subsisting on a few hundred dollars per year or less. Electricity's role will be to provide an essential foundation for economic development and to bring improvements in the efficiency of resource utilization. Global electrification, which has the potential for reducing resource consumption growth by as much as 50% by 2050, is the most efficient energy pathway for sustainable growth.

One possible showstopper would be the diversion of scarce financial resources to satisfy near-term climate policies, inadvertently slowing down the rate of innovation and productivity growth and effectively freezing energy technology at inadequate performance levels.

The technology opportunities and knowledge gaps related to global sustainable growth begin with the electricity infrastructure because of the critical role it plays in economic growth and the energy and economic efficiencies it enables. Some additional sustainability-related opportunities include:

- Large-scale rural and village electrification using a portfolio of low-cost distributed generation options
- Environmentally improved methods for solid fuel and biomass utilization, particularly in developing countries
- Electrotechnologies that improve the efficiency of agriculture, land, and water usage
- Electrified transportation and lower-cost, streamlined service infrastructure for urban and intercity use

Global Energy System and Environmental Benchmarks

Starting from the Roadmap destinations and assumptions about population and economic growth, it is possible to develop a composite picture of preliminary benchmarks for global energy systems and the environment over the next decades. These benchmarks were initially derived from United Nations Development Project (UNDP) and World Energy Council (WEC) data and scenarios, but were modified to reflect the impact of

DESTINATIONS AND TECHNOLOGY TRENDS

The body of this report focuses on the ways in which technology advances can help achieve the Roadmap destinations. In developing the linkages between technologies and destinations, the participants noticed that certain technology trends or drivers have a strong enabling role for more than one destination. The science and technology drivers that will have the strongest influence on achieving the Roadmap destinations are:

- Distributed power generation that moves closer to the end user with ever-greater conversion efficiency
- Power electronics that can improve power quality and reliability while handling the dramatic increases in power flow and power market transactions
- Microprocessor-based electrotechnologies that provide a quantum leap in electricity's efficiency and precision advantages
- Real-time information technology advances that enable ever-larger supply and service networks and redefine the relationships between customers and providers to increase market transparency
- Advanced materials with improved properties to enable, for example, more efficient power electronic devices and solar photovoltaic cells, high-temperature and radiation resistance for power generation applications, recyclability to reduce resource consumption, and adaptability to meet changing conditions without redesign or redundancy
- Biotechnology applications for productivity improvement (biological computer systems, biomimetic processes) and bio-solutions to the challenge of sustainable growth (carbon sequestration methods, biomass crops for electricity generation, higher agricultural productivity, bioremediation of contaminated sites, etc.)
- Rapidly expanding environmental knowledge of the impact of human activity on the planet, reflected in technologies that minimize adverse consequences for current and future generations

The synergistic nature of these technology drivers is shown in Table 1-1. In this table, a large circle indicates that the enabling technology is likely to have a strong influence on a particular Roadmap destination, and a smaller circle indicates a lesser, but still significant, influence. Each of these technology drivers has a potentially strong impact on at least three of the destinations. It is recommended that research priorities reflect these correlations.

Table 1-1 Destinations and Technology Drivers

Science and Technology Drivers	Strengthening the Power Delivery Infrastructure	Enabling Customer-Managed Service Networks	Boosting Economic Productivity and Prosperity	Resolving the Energy/Carbon Conflict	Managing the Global Sustainability Challenge
Distributed Generation	●	●	●	•	●
Power Electronics	●	●	●	•	●
Microprocessor-based Electrotechnology	•	●	●	●	●
Real-time Information Processing Technology	●	●	●	•	●
Advanced Materials	●	•	●	●	●
Biotechnology	•	•	●	●	●
Environmental Knowledge and Technology	●	•	●	●	●

advanced technologies identified by the Roadmap participants. In particular, the Roadmap proposes the goal of converting at least two-thirds of the world's primary energy consumption to electricity by 2050, up from just over one-third today. This goal would afford essential economic growth while moderating the primary energy requirements and environmental impact historically associated with such growth. Achieving such a goal would be the most effective means of providing the clean, efficient energy needed by the world's 10 billion people, while substantially reducing the growth rate of primary energy consumption. However, this will require a focused worldwide effort to increase the efficiency of converting all energy forms to electricity, improve the environmental performance of electricity systems, and provide the 10,000 GW of new electricity generating capacity needed over the next 50 years.

Table 1-2 summarizes these benchmarks, using nominal values for parameters that are particularly sensitive to exogenous conditions. Note that in the future, population, productivity, and the electricity fraction of total energy are expected to increase, while energy intensity is expected to decrease. The actual trend in generation capacity will be sensitive to these constituent factors, as well as to future technology developments. For example, electrifying transportation could increase the estimate of electricity consumption by up to 15% (10 $x10^{12}$ kWh) in 2050 with a corresponding decrease in petroleum dependency. This does not necessarily mean, however, a corresponding increase in traditional electricity generation, given the anticipated progress in mobile power production and storage technology.

These benchmarks are intended to be a point of departure for the specification of global energy requirements for 2050.

The Technical Priorities

The Roadmap has begun to assess required cost-performance characteristics of a range of technologies critical to reaching the five destinations. The picture that emerges over time is as follows:

Table 1-2 Preliminary Benchmarks for the Global Energy System and the Environment

	2000	2020	2050
Assumptions			
Population (billion)	6.2	8	10
Gross World Product, $trillion (1990)	32	50	100
Energy System Benchmarks			
Primary Energy, Gtoe per year (gigatonnes of oil equivalent)	10	13	17
Energy Intensity, Gtoe/$trillion	0.31	0.26	0.16
Electricity Fraction of Primary Energy	0.38	0.5	0.7
Electricity Conversion Efficiency (global average)	0.32	0.4	0.5
Electricity End-Use Consumption (trillion kWh per year)	13	28	60*
Electricity Generating Capacity, (thousands of gigawatts)	3	5	10
Cost of Worldwide Universal Service, 1990 $/kWh	0.13	0.10	0.05
Environmental Benchmarks			
Maximum Carbon Emissions, Gt per year	7	8	7–10
Other Emissions	Declining	Minimal	Minimal
Waste Streams	Declining	Minimal	Minimal

**Includes 10 x 10^{12} kWh for electricity-based transportation*
Sources: UNDP, WEC, DOE/EIA, EPRI analysis

In the near term of the next decade, the focus should be on:

- Broad implementation of silicon- and post-silicon-based power electronic systems for monitoring and control of the power delivery system

- Integration of distributed generation and local storage into a new grid architecture appropriate for a competitive marketplace
- Creation of new, interactive, customer-managed service capabilities
- Accelerated global deployment of the cleanest and most energy-efficient fossil-based power production technologies
- Development and initial deployment of environmentally superior energy systems designed for affordable use by developing nations
- Acceleration of R&D on potential breakthroughs in renewable and nuclear power generation
- Acceleration of R&D on end-use energy efficiency and productivity-enhancing technologies, including larger-scale storage capabilities

In the midterm of the two or three decades beyond, that established base could be steadily expanded to achieve:

- Accelerated global electrification of industry and transportation for improved efficiency, productivity, and environmental protection
- Revitalization of the nuclear power option and the introduction of low-cost renewable generation capable of meeting global electrification requirements
- Deployment of robust, grid-level power storage capabilities to improve the reliability, flexibility, and quality of electricity service
- Streamlined, higher-efficiency, and lower-cost designs for urban services infrastructure; encompassing energy, communications, transportation, water, and sanitation

In the long term of mid-century and beyond, the goals should be:

- Worldwide universal electrification to achieve more efficient use of energy, land, and water; and to minimize waste streams from industry, agriculture, and cities to create the framework for a sustainable future

Table 1-3 Estimated Funding Requirements for the Roadmap-Recommended Research Program			
Destination	**10-Year Funding Outlook ($ million/yr)**		
	Current Funding	**Additional Funding Needs**	**Total Funding Needed**
Power System Vulnerability	400	600	1,000
Customer-Managed Service Networks	400	500	900
Boosting Economic Productivity and Prosperity	700	1,500	2,200
Energy/Carbon Challenge	1,600	2,000	3,600
Global Sustainability Challenge	N/A	to be determined	to be determined
Total	**3,100**	**4,600**	**7,700**

- Global deployment of high-efficiency electricity production and delivery systems to reduce the costs and improve the environmental performance of the expanded electricity infrastructure
- An ever-greater portion of energy derived from nuclear and renewable sources to reduce carbon emissions and global dependence on nonrenewable sources

As a first step toward achieving these goals, Table 1-3 provides a preliminary estimate of the U.S. R&D funding needs for these destinations over the next 10 years. The total U.S. funding required for this technology development package, exclusive of the global sustainability destination, is about $7.7 billion per year, an increment of about $4.6 billion per year over current levels. This represents an addition of approximately 2% to current U.S. total R&D expenditures for all fields of science and technology. Less than one-half of the needed R&D is under way, and significant portions of the programmatic needs are currently unfunded. In some cases, redirection of existing funds should also be considered to improve their effectiveness. Additional detail on the funding needed to address key knowledge gaps is outlined in the following chapters of this report. In each case, the ability to provide the necessary technical tools in the timeframe needed requires urgent action.

It is particularly difficult to estimate the science and technology requirements for the global sustainability destination. Current research funding levels in this area are not well defined, largely because the relevant work is being performed throughout the world in an unstructured manner via a host of diverse projects and under a wide variety of topical titles. Looking toward the future, sustainability research is expected to expand at the global, regional, and local levels, particularly through multilateral alliances involving both the public and private sectors. The total funding requirements to achieve the technology needed for sustainability in the 21st century are certainly in the multibillion-dollar-per-year level. However, confident estimates will require scoping studies to prioritize and cost out the key knowledge gaps. A global collaborative effort is recommended, integrating developed and developing country perspectives as the essential first step to identify the needed funding requirements and to develop coordination and implementation mechanisms.

But any reasonable estimate of the total research funding requirement is minuscule in comparison with the growing gross world product now exceeding $30 trillion per year. This suggests that mustering the political consensus to invest in the necessary, broad-based collaborative program, and to implement its results, is likely to be a greater challenge than the scale of needed financial and human resources.

A number of requirements permeate all paths and all timeframes of the Roadmap. The most apparent is the need for a comprehensive and imaginative body of both directed and exploratory research, supported at a significant level. There is no deterministic program that can prepare for all contingencies; the only truly renewable resource relevant to this problem is human creativity liberated by education and investment.

Facilitating Initial Roadmap R&D Activities

Neither government nor industry can fulfill the Roadmap's vision alone. The Roadmap participants identified a need for a major increase in electricity-related R&D investment at

THE ROADMAP PROCESS

The Roadmap was initiated to allow energy stakeholders to explore desirable possibilities for the future and create a plan for making those possibilities a reality. The creation of the Roadmap began with the exploration of opportunities in five distinct topical areas:

- Sustainable global development
- Electricity and economic growth
- Power delivery infrastructure
- Power production
- Environmental knowledge base

For each area, in-depth discussions were undertaken in small groups and larger workshops over the course of the past year. The participant-experts evaluated and prioritized pathways to achieve the larger vision and identified the critical knowledge gaps that would have to be closed in their respective topical area. Module reports from these five teams are available. Key findings are summarized in Appendix C of this report. After the five interdisciplinary teams developed their perspectives, a plenary group was brought together to synthesize the results and establish a coherent set of goals and recommendations for achieving these destinations.

The Roadmap is a work in progress that will be steadily updated to incorporate new possibilities, technical innovations, and changing priorities. The Roadmap process allows participants to:

- Articulate their aspirations for increased prosperity, quality of life, environmental protection, and global sustainability
- Identify the roles for electricity innovation in achieving these destinations
- Define the critical scientific and technical gaps that must be filled to reach the destinations
- Establish a comprehensive research agenda for satisfying these gaps
- Promote the public/private partnerships essential to implementing this research agenda

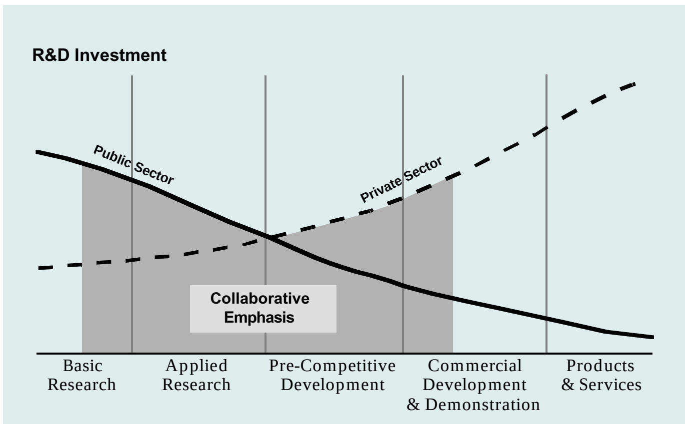
Further, all participating organizations gain from working together to establish a continuing collaborative development process. The continuing process will focus on:

- Communicating the key Roadmap findings to the broad group of stakeholders
- Developing specific R&D agendas needed to achieve the destinations of the Roadmap
- Implementing the Roadmap recommendations in both the public and private sectors
- Updating of the Roadmap as new knowledge becomes available and as priorities and destinations change

Testing of the Roadmap vision, destinations, and specific technological opportunities is a crucial step. This will require broad engagement by public and private organizations, including federal and state legislative and regulatory bodies, national laboratories, academic researchers, and private industry, as well as representatives of the electricity enterprise throughout the world. The Roadmap Initiative expects to convene further working sessions and reach out to an even broader range of stakeholders and experts to construct the most confident and comprehensive R&D response.

a time when there are many competing needs for both public and private funds. In the coming year, the Roadmap participants expect to focus on the specific R&D agendas and on identifying new opportunities for building the needed public/private consortia.

Public/private R&D collaboration can facilitate the transition from basic research to the competitive marketplace.



Policymaker involvement will be an important component of Roadmap implementation. Issues include the loss of R&D incentives, the potential inefficiencies of fragmented and uncoordinated local R&D initiatives, and the policies needed to offset the impact of industry restructuring.

Particularly important to progress will be the creation of new financial incentives for participation in public/private collaborative R&D initiatives to share the costs and risks of strategic technology development. Such incentives could include tax credits for research, innovation, capital investment, production, and environmental improvement; enhanced intellectual property protection; market stimulation and procurement policies; and streamlined regulatory processes to facilitate needed innovation. In areas such as energy efficiency and power system reliability, establishment of more comprehensive minimum performance standards and specifications may also be considered, together with clear placement of responsibility and access to resources for meeting those requirements.

Conclusion: Beyond Electricity

This initial Electricity Roadmap effort illuminates profound opportunities for electricity and innovation to power progress—for the U.S. and for the world. Its vision goes far beyond electricity as just a form of energy. It merges power with the information revolution, and the numerous innovations enabled by and dependent upon this new mega-infrastructure. This integrated portfolio of opportunities and potential innovations can benefit humanity everywhere. Its success will fuel the development of global markets and accelerate economic growth, while protecting the environment and broadening the base of human opportunity.

The Roadmap addresses the challenges of investing today in the research that will lead to societal benefit tomorrow. Nathan Mhyrvold, Chief Technology Officer of Microsoft Corporation, recently summarized this challenge:

> *Will the final days of the 20th century be as auspicious as those of the 19th? Although the opportunity is clearly there, it is hard to muster the unbridled optimism of the earlier age. As a society we are shirking our support for basic science at the very time when our previous support is reaping great returns. In doing so, we jeopardize not only our legacy of scientific achievement, but also the economic prosperity of the near future. It is clear that we* ***can*** *afford to spend more on science. It is also clear that we* ***need*** *to spend more if we want to continue to enjoy a technologically based economy. The missing elements are the will and the vision to bet on the scientific enterprise, vital to the realization of the full potential of the next millennium.*

As the most versatile and advanced energy form, electricity is essential in virtually all our activities and will be even more so worldwide in the coming century. The Roadmap illustrates an unprecedented window of opportunity to use electricity-enabled science and technology innovation to build prosperity and quality of life on a global basis. But broad commitment is urgently needed if these opportunities are to be realized.

2 The Power System Challenge

...Building the Infrastructure of a New Industry

The Roadmap's pathway to the future begins with one of the most fundamental of electric utility functions: getting electricity from the point of generation to the point of use. Power delivery has been part of the utility industry for so long that it is hard to imagine that this process has not already been optimized. However, the power delivery function is changing and growing more complex with the exacting requirements of the digital economy, the onset of competitive power markets, the implementation of modern distributed and self-generation, and the saturation of existing transmission and distribution capacity. Without accelerated investment, the reliability of the power system will almost certainly degrade, such that the losses due to transmission and distribution interruptions can outweigh the anticipated economic benefits.

Vulnerabilities Due to Changing System Use and System Interdependence

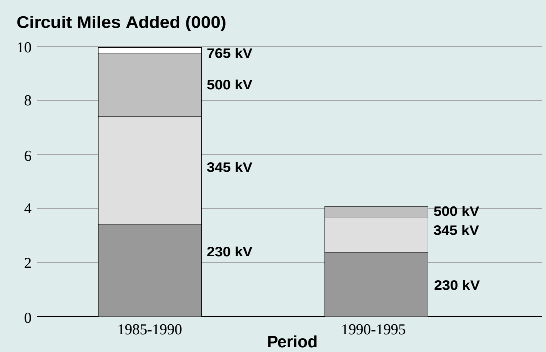
The value of bulk power transactions in the U.S. has increased four-fold in just the last decade, so that about one-half of all domestic generation is now sold over ever-increasing distances on the wholesale market before it is delivered to customers. This growth, however, comes at a time when many parts of the North American transmission system are already operating close to their stability limits, as illustrated by recent widespread outages in the Western states. The cost of the August 10, 1996, outage in California alone was estimated to be nearly $1 billion. Traditionally, utilities would be adding new transmission capacity to handle the expected load increase, but because of the difficulty in obtaining permits and the uncertainty over receiving an adequate rate of return on investment, the

The explosive growth in bulk power transactions is increasing the demand for transmission system access.

total of transmission circuit miles added annually is declining while the total demand for transmission resources continues to grow. In many cases, de facto restructuring policies actually disguise market signals and compromise incentives for investing in transmission system upgrades. In addition, system planning by the regional transmission operators (RTOs) is slowed because of the cooperation required with transmission owners and the dependence on investor decisions concerning the location and timing of new generation.

In assessing the impacts of market and technological change, it is convenient to view the electricity infrastructure as two tightly coupled networks. One is the physical network of power generation, delivery, and end use—the electric power system. The other is the underlying data network, including the information processing systems that are critical to safe and reliable operation of the power grid and management of grid-related financial transactions. Problems with one of these networks will usually create problems with the other, and proposed solutions to these problems must consider the complex interactions within and between the elements of the power and data networks.

Although demand is increasing, transmission capacity additions are declining.

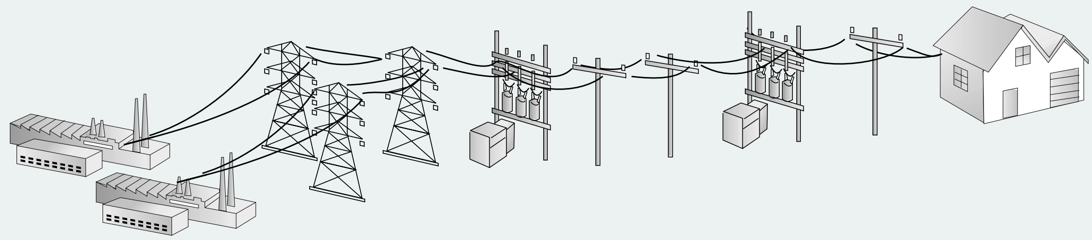


Source: Cambridge Energy Research Associates

In addition, other infrastructures, including transportation, telecommunications, oil and gas, and financial systems, depend on the electric power infrastructure to energize and control their operations. This dependence means that failure in one sector can easily propagate to others, multiplying the damages associated with system failures.

Technological solutions to electricity delivery system problems are under development and are described later in this chapter. However, broad commercial implementation of these solutions is being delayed until restructuring policies encourage greater investment in the power grid—or at least do not discourage investment. Until then, the risk of major power interruptions will grow, decreasing confidence in the grid.

TODAY'S POWER SYSTEM



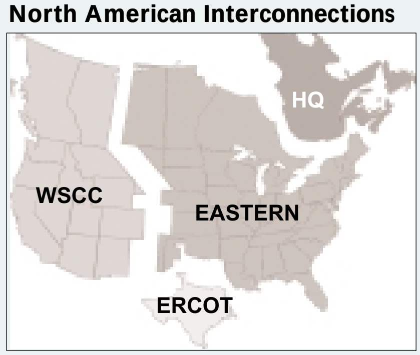
Our electric power system today consists of power generating plants, a transmission network, local distribution systems, and associated control centers. The interconnection of transmission lines forms the "power grid" that permits the movement of electricity from power generators to distributors via multiple paths. Altogether, the nation's transmission system includes over 670,000 miles of electric lines of 22,000 volts or greater.

The North American power grid is divided into four regions for operational purposes, as shown on the map below—Eastern, Western, Texas, and Quebec. The flow of power within individual regions is growing fast as the U.S. power market restructures, with buyers and sellers seeking the best deals across ever-increasing distances. Within each region, control centers monitor generating plants, delivery systems, and customer demands. Interregional transfers are limited by the availability of DC links.

Transmission lines end at substations where the high voltage of transmission is reduced to primary distribution voltage levels. This lower-voltage power is then supplied directly to large industrial users or further reduced at other substations for local distribution.

Loss of reliability has far-reaching consequences, such as loss or damage of electronic data, lost production, and restoration costs. Apart from maintenance and repair, reliability depends on keeping the speed of the generators and the voltage of the lines stable within very narrow limits. This requires precise control of power flows throughout the system to match the demands for power. Ever more sophisticated power plant dispatching and electricity flow control is needed, particularly as the nation's emerging competitive power market encourages broader dispersion and ownership of generators, higher and less-predictable line loadings, and a vast increase in transactions. A fundamental issue with competitive restructuring concerns how to decentralize decisions on generation and load while maintaining the essential complementary relationship between generation and transmission.

North American Interconnections



Source: Hyman, America's Utilities: Past, Present and Future

Vulnerabilities Due to Scale and Complexity

The U.S. electric power system is one of the largest and most complex machines of the technological age. Managing this system will become increasingly difficult as overall loading continues to grow with deregulation. The Energy Information Administration (EIA), for example, predicts a 15% increase in demand over the next decade. Moreover, a growing fraction of this electricity will serve the highly sensitive electronics of the digital economy, thus placing an additional premium on reliability and quality of service. Improved models and tools are needed to deal with system complexity because without additional aid, operations staff will not be able to respond quickly enough to detect and correct problems. The large-scale and real-time distributed control requirements of the power system will increasingly challenge the state of the art in transmission and distribution system management.

The complexity of the electric power system, combined with its large geographic extent, makes it vulnerable to natural events, human error, and intentional attack. The industry has a great deal of experience in dealing with the first two of these, and recently has begun considering the urgency of protecting the physical assets of the power system against attack by terrorists or saboteurs. Perhaps even more difficult to protect against would be cyber attacks on the computers and software used to handle the growing number of power transactions and the operation of the physical grid. Trends toward standardization of computer and software systems may inadvertently increase vulnerability to cyber attack.

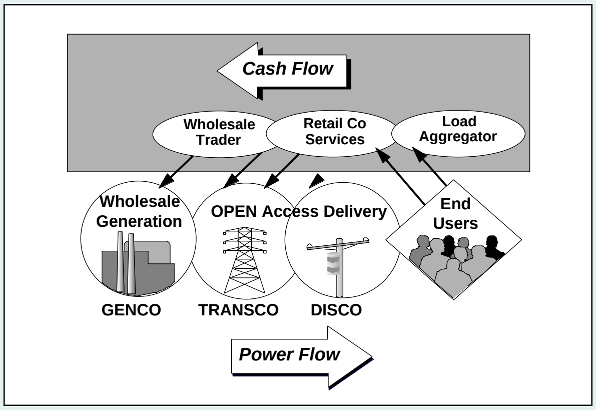
Interdependent Infrastructure Driving the Need for Collaboration

In the electricity industry of the future, it's likely that every utility computer will be connected to every other computer in the energy/information network. Although these interconnections increase vulnerability to human error and intentional attack, they also create a situation that strongly favors collaboration to address the common problems of computer security, both within the electricity industry and between electric power and other industries.

RESTRUCTURING FOR COMPETITION

Electric power industry restructuring is the biggest and most complex industrial reorganization of the postwar period. Why the change? The answer lies primarily in technology, not ideology or politics. For most of its history, the electric power industry consistently exhibited economies of scale; as newer and larger power plants were added, the overall cost of electricity kept declining. But in the late 1970s, average costs began to rise due to factors such as higher fuel prices, new emissions control equipment requirements, nuclear plant construction and operations difficulties, and the push for higher-efficiency plants.

Evolving U.S. Utility Industry



Then a major change occurred. Against most predictions, large amounts of low-cost natural gas were discovered—along with new low-cost, quickly built combustion turbines utilizing aircraft engine technology to turn it into electricity. But electricity demand was growing only slowly, and utilities couldn't build many new gas turbines while using and paying for their existing plants. Customers, especially in high-cost states, quickly grew impatient. Both federal and state governments began taking steps to relieve policy constraints on natural gas use and to allow independent firms to build new power plants and find a market.

Now industry restructuring is spreading state by state across the country, possibly to be augmented by federal legislation. Competition is being encouraged at both the wholesale and retail ends of the electricity market. Statewide or regional organizations will supervise this market and the transportation of the electricity. Utilities may operate regulated distribution systems as before; but production, brokerage, and sale of energy as well as services are becoming competitive functions.

Major technological changes will be needed to accommodate this new open-market approach. Above all, system reliability must be assured despite vastly more complex operations, including huge volumes of hourly and daily transactions and far more participants in the movement of power from sources to users. Despite this new complexity, the system must meet all anticipated demands economically and keep power flow stable by compensating instantly for unexpected demand, outages, and all other emergencies. Large investments in innovation and installation of new power delivery technologies will be essential.

Competition is forecast by DOE's Energy Information Administration to produce direct savings of at least \$25 billion per year to the U.S. economy. But these benefits depend on the continued reliability of an extraordinarily complex electricity network. Degradation of the system's present performance could be extremely costly, offsetting a year's competition savings in a matter of a few days.

The New Electric Business Structure		
U.S. GDP (1998)	\$8.5 x 10^{12}/year	(100%)
Electricity Industry Revenues (1997)	\$220 x 10^{9}/year	(3%)
Expected Direct Savings from Restructuring	\$25–50 x 10^{9}/year	(0.3–0.7%)
National Power Outage Cost	**~\$25 x 10^{9}/day**	

Interconnections create a situation that strongly favors collaboration.

This cross-industry collaboration is already beginning. The President's Council on Critical Infrastructure Protection has spawned several strategic planning studies, including one on the electric power sector. This initiative identified the following technology and policy objectives:

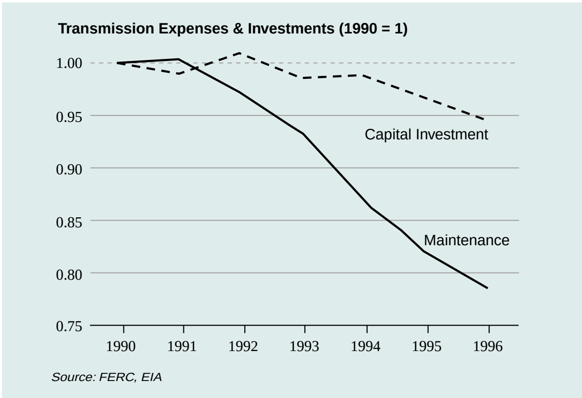
- **Balance public and private interests in the nation's electricity supply.** Ensure that public policy, roles, and responsibilities will guarantee the public good, while permitting free market forces to serve private interests.
- **Guarantee the safety, availability, and quality of the nation's electric power grid**. Continue fundamental research to understand, create, and apply power technology products and management tools critical to the reliability of the power grid.
- **Guarantee the integrity, confidentiality, and availability of the information network.** Research, develop, and apply secure, robust, and adaptive information systems, network technologies, and management tools.
- **Increase assurance of interdependent infrastructures.** Increase understanding of what each infrastructure owner/operator must know about other infrastructures to enable rational contingency planning. Develop new cooperative agreements within the electric power industry and between interdependent private and public service providers.

These objectives illustrate the importance of combining technology and policy concerns to develop an effective plan of action for improving the reliability and security of the power system. Unless resolved, these issues will increasingly constrain transmission systems from serving as effective enabling platforms for competitive power markets.

Stagnation in delivery infrastructure investment is occurring as both public/private roles and owner/operator roles are being debated.

The technology opportunities outlined in this chapter can only be achieved in a favorable investment climate; that is, one in which the incentives, business models, and institutional roles under deregulation are clearly established. In such a climate, improvements to the system can be made progressively, with the new technologies and the products and services they generate phased in as they make good business sense. It is notable in this environment that four of the five power electronic systems in the U.S. based on Flexible AC Transmission System (FACTS) technology to facilitate wholesale competition and reduce grid congestion have been installed by public power utilities.

Both capital investments and annual maintenance expenditures have been trending downward in recent years.

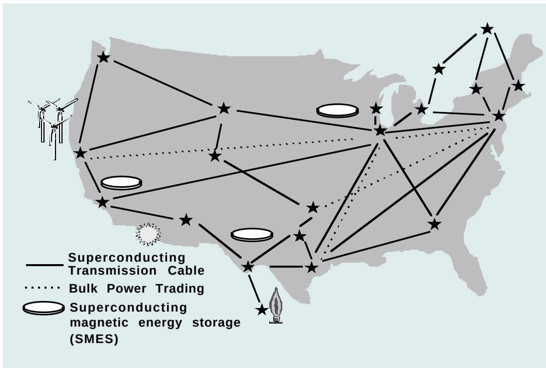


However, if and when such issues are resolved, and if both development and deployment investments are made in a timely manner, there is every confidence that a robust power delivery system capable of keeping pace with a universal digital economy can be achieved. The upgraded delivery system will be a necessary key to helping the U.S. sustain robust economic growth and its leadership position in the world.

In addition to transforming the U.S. grid, technology advances could spearhead the creation of streamlined transmission systems in developing nations, with both long-distance and urban delivery capabilities. These advances will enable new business opportunities in power marketing, long-distance power transmission, and end-user services in the most rapidly growing regions of the world.

However, efforts to enhance economic growth and quality of life in developing countries must recognize that economic development and business opportunities will increasingly depend upon reliable power. Previous efforts, which focused simply on increasing the availability of electricity, have proven only partially successfully, as the often low-quality, intermittent and/or unreliable electricity service provided frequently did not meet real needs. The World Bank estimates, for example, that 92% of manufacturing firms in Nigeria purchase power from private sources because the public power supply is chronically unreliable. The opportunity cost of poor-quality electric service to the Nigerian economy reaches about $1 billion/year. Similarly, the World Bank describes firms in Indonesia willing to pay generation costs exceeding $2/kWh to assure high-quality power. Related studies in Latin America estimate that power shortages and interruptions cost the regional economy $10–$15 billion annually.

Emerging technologies will shape the design of the power delivery system of the future.



Technologies for the Power Grid of the Future

Before 2010, the Roadmap envisions the capability to achieve a unified, digitally controlled transmission grid to move large amounts of power precisely and reliably throughout North America, while managing an exponentially growing number of commercial transactions. In effect, the grid becomes an Internet for electrons. New technologies that can enable this capacity are emerging. Thus, the opportunity exists not only to solve the current slate of problems, but also to create a new infrastructure that will support the exacting needs of the digital economy, as well as the growing quality of life aspirations for the 21st century.

Optimizing the fundamental transmission stability parameters of impedance, phase angle, and voltage support will allow the system to operate closer to its thermal limits, thereby technologically expanding the grid's capacity while delaying the need for new transmission lines. The backbone of the envisioned grid will consist of an enhanced overhead system, augmented by more cost-effective underground "high-temperature" superconducting (HTS) and advanced polymer cable systems. Power flow management based on power electronic devices and wide-area communication and control technologies will be employed to eliminate transmission bottlenecks and address stability concerns. The improved grid will link power generation to the customer over longer distances, thus contributing to the flexibility of supply. It will also be capable of providing customer access to more diversified generation sources and to resources that would otherwise be wasted (e.g., flare gas in Mexico). With proper incentives and investments, all customers can have access to the power quantity and quality they need at any time of day at the lowest available cost. Moreover, increased undergrounding of transmission and distribution will reduce outages and hostile-threat exposure, decrease exposure to electric and magnetic fields

With proper incentives and investments, all customers can have access to the power quantity and quality they need.

(EMF), and limit the visual impact of the power system. These technology advances could also create a new equilibrium between AC and DC power transmission, improving both stability and power transfer.

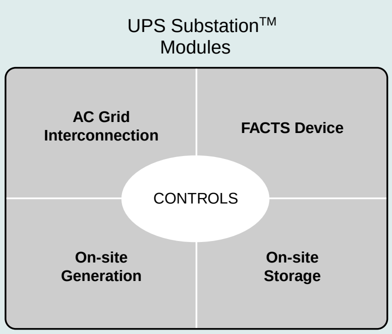
The following critical technologies are needed to create the transmission grid of the 21st century:

Flexible AC Transmission System (FACTS) This family of high-voltage electronic controllers can increase the power-carrying capacity of individual transmission lines and improve overall system reliability by reacting almost instantaneously to disturbances. Electromechanical controllers used today are too slow to govern the flow of alternating current in real time, resulting in loop flows and bottlenecks. By acting quickly enough to provide real-time control, electronic FACTS controllers can increase or decrease power flow on particular lines, alleviating transmission system congestion. In addition, these controllers can enhance system reliability by counteracting transient disturbances almost instantaneously, allowing transmission lines to be loaded closer to their inherent thermal limits, effectively increasing their capacity. As FACTS devices are extensively deployed throughout the North American grid, system operators will be able to dispatch transmission capacity within the primary interconnection regions, thus facilitating open access.

Electronic FACTS controllers can enhance system reliability by counteracting system disturbances almost instantaneously.

After nearly 20 years of R&D, FACTS controllers based on silicon power-electronics devices are now entering utility service. One recent example is the unified power flow controller (UPFC) brought on-line in 1998 at American Electric Power's Inez substation. The latest FACTS device is the UPS Substation™, which provides instantaneous and continuous power at a transmission station even when the grid is down, effectively allowing power conditioning to move upstream from the customer. The UPS Substation™ integrates several advanced

A new uninterruptible power system (UPS), designed for use at substations, effectively allows power conditioning to move upstream.



Trademark of The Electric Power Research Institute modules, including FACTS, distributed generation and/or energy storage, plus system controls and AC interconnection. At the 20-MW power level, estimated costs range from $250 to $450/kW.

The major developmental challenge now is to reduce the cost of FACTS systems to achieve the needed widespread utility use. New wide-bandgap semiconductor materials—such as silicon carbide, gallium nitride, and thin-film diamond—could dramatically lower the cost of FACTS devices by providing the basis for developing a power electronic equivalent of the integrated circuit. Demonstration of a Fast Turn-Off Thyristor based on wide-bandgap semiconductors could take place as early as 2001. The Fast Turn-Off Thyristor will also reduce the cost of AC/DC converters for making DC interconnections between asynchronous AC power systems and for increasing the use of long-distance DC transmission.

Large-scale transmission applications of superconducting cables are expected by 2010.

High-Temperature Superconducting (HTS) Materials HTS materials that essentially eliminate electrical resistance at liquid nitrogen temperatures were discovered in 1986. Since that time, research has focused on improving the fundamental understanding of the phenomenon, identifying new HTS materials, and making a flexible wire or cable out of what is a brittle ceramic. Development has progressed to the point of small, distribution-system-scale demonstrations, such as the demonstration of a 3-phase, 24 kV cable being installed at Detroit Edison. Large-scale commercial transmission applications are expected by about 2010. The major advantage will be the ability to conduct up to three times as much electricity within the existing conduit.

This and other demonstrations will provide vital experience in handling and characterizing HTS cables, but further development is required before these cables are cost competitive and the benefits of the technology can be realized. These benefits include lower-voltage transmission, lower-cost substations, lower power losses, and improved power quality. Realizing the full advantages of HTS technology in transmission system applications also requires further development and demonstration of supporting technologies such as cryogenic cooling systems and low-cost methods for underground installation. Typically, construction can account for up to 70% of the total system costs for underground transmission. Guided boring systems that eliminate the need for trenching are under development to meet the need for reduced cost.

Polymeric Cables Even as HTS cables are introduced, there is an increased need for overhead and underground conventional cables that are better able to tolerate high stresses during emergency overload conditions. Polymeric cables now under development will prevent the cavities and expansion that occur in conventional cables during overload conditions. Prototypes of high-performance polymeric cables are expected to be demonstrated around 2000, with commercialization to follow. Widespread commercial use could be achieved by around 2010.

Online Analysis and Control The first Wide-Area Management System (WAMS) based on satellite communications is currently being installed in the western U.S. power grid. The safe and reliable operation of the expanded transmission system will require better integration of the physical grid with the control network. The new science of complex adaptive systems, coupled with anticipated improvements in computing power, can make possible high-fidelity modeling of system response in near real time. This will give operators the information they need to prevent cascading failures—and give customers the service they are demanding.

Bulk electricity storage is urgently needed.

Energy Storage New energy storage technologies will play an important role in facilitating the development of a continental power market. Some technologies for electrical energy storage have a history of long-standing but limited use. Relatively inexpensive, large-scale technologies—such as pumped hydro—can provide extra energy to meet peak demand, but cannot respond rapidly enough to counteract transient disturbances. On the other hand, storage technologies with rapid response times—such as batteries—have until recently been too expensive for widespread use in peak shaving.

As bulk electricity is increasingly sold as a commodity, the need has become more urgent for new storage technology that is both fast and inexpensive. Diurnal or longer-term energy storage will revolutionize electricity markets and commodity trading. Industry experience with pumped hydro and compressed air energy storage (CAES) will form the basis for future development of viable large-scale storage systems. Interest in these technologies will increase as the industry gains experience with power markets and begins to quantify the risks and rewards of investing in storage technologies.

Hydrogen is the ultimate long-term electricity storage solution.

Ultimately, long-term storage will probably be achieved by using hydrogen as a storage medium. Hydrogen, produced electrolytically during off-peak hours, could be used for peak shaving during periods of high demand. It also is the favored fuel for fuel-cell automobiles, as discussed in Chapters 3 and 6. However, technology gaps must be closed to enable broad utilization of hydrogen as an energy carrier. Beyond improving the storage density of hydrogen, it is critical to demonstrate the ability to handle hydrogen safely. Currently, hydrogen is stored in on-board tanks pressurized to ~5000 psi. The tanks are bulky and difficult to handle, and the high pressure level raises safety concerns. One solution proposed, using metal hydrides to increase the storage density, has given rise to a new set of safety concerns related to the possible formation of a finely divided, easily ignited powder through repeated charging and discharging of the metal hydride system. Current R&D is directed at using carbon nanotubes as the storage medium. Early studies have shown promising results, but more work is needed to reliably demonstrate the capability of this approach.

Storage technology is also needed to improve power quality by preventing and reducing the impact of short-duration power disturbances. Low-temperature superconducting magnetic energy storage (SMES) is already being used to provide brief, instantly available ride-through capability for sensitive equipment on lines subject to interruption. However, economies of scale quickly limit the ability of current technology to support an entire distribution system during periods of peak load. Multiple storage technologies will probably be needed to meet the power quality needs of various segments of the market. A major recent breakthrough is the development of a transportable battery energy storage system (TBESS), which entered utility service in 1997. This flexible system operates in two modes. It can provide short-duration power (2 MW for 15 seconds) to protect against outages caused by faulted lines. Alternatively, it can provide 200 kW continuously for 45 minutes, thus facilitating peak shaving.

For delivering power levels of 10–100 MW for periods up to a few seconds, SMES is currently the preferred storage technology, with flywheels offering a possible alternative. The first demonstration of an HTS/SMES (using HTS for energy storage) may come as early as 2003. Demonstration of flywheel storage could also occur by 2003. Flywheels appear suitable for providing tens of megawatts for periods ranging from several seconds to a few minutes.

Technologies for a Revolution in Electricity Distribution

By 2020, the demand for premium power—now just developing—will be pervasive throughout every sector of the economy.

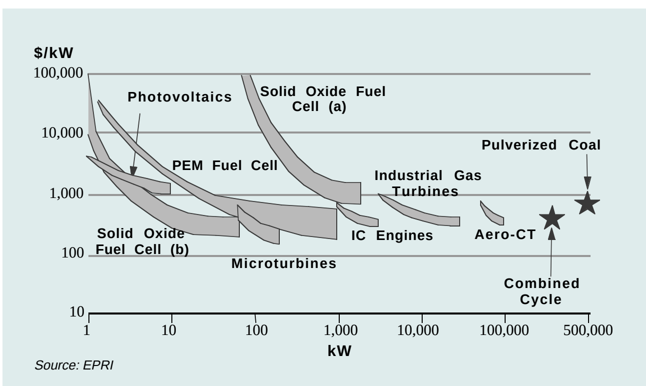
In addition to making changes in the wholesale market, several states have begun to implement retail access programs, which will provide consumers a choice among electricity providers. Power quality and reliability requirements are increasing for industrial and commercial customers, and a market is developing for "premium power" to serve the most demanding customers (e.g., those dependent on digital microprocessor systems). By 2020, this demand will likely be pervasive throughout every sector of the economy. In fact, less than perfect power comes at a very high price in a digital economy. More and more, customers with critical power quality needs will find it necessary to self-generate if they cannot get the quality they need from the grid. The Roadmap therefore envisions the ability to deliver electric power of any waveform, quality, and reliability at a price providing increased net value to the users. This capability could function with, and be partially derived from, extensive distributed resources interconnected with the distribution grid. Technical innovations now on the horizon could make possible an unprecedented level of system integration within 10 years. This in turn would allow the distribution system to become a comprehensive common carrier as retail competition expands.

Achieving this destination will require accelerating three paths of technological development already underway. The first is distribution automation, based on advanced sensors and control software to improve power suppliers' ability to detect and correct disturbances more quickly, thus reducing customer outages and power quality problems. This will lead to automated isolation and restoration capabilities, by about 2005.

The second technology development path is Custom Power, a family of power electronic controllers designed for service on distribution systems. These devices and systems can provide real-time network control, protect sensitive customer equipment from network disturbances, and protect distribution feeders from power disturbances arising on the customer's premises. Custom Power systems improve power quality for customers with special needs—for example, an industrial park with high-technology companies.

The third path is the development of generation and storage technologies for distributed applications. These devices will move the power supply closer to the point of use, enabling improved power quality and reliability, and providing the flexibility to meet a wide variety of customer and distribution system needs.

We should see substantial reductions in the cost of distributed resources over the next decade.



Distributed Generation

Revolutionary advancements appear likely in the field of distributed generation over the next 10 years and beyond. Distributed generation close to the point of use reduces the need for T&D investment, while resolving many system constraints and eliminating line losses. Many distributed generation technologies also produce recoverable heat suitable for cogeneration, thus improving overall efficiency and contributing to both economic and environmental value. Microturbines in the size range of 20–75 kW are commercially available, but their stand-alone efficiency is rather low (22–33%, based on the lower heating value). Improving their efficiency (and using them in cogeneration applications) will make microturbines attractive alternatives to grid-based electricity and services. Fuel cells, an option without moving parts, has the potential for higher conversion efficiency and nearly zero emissions. However, both initial and operating costs are high today, and the Roadmap identifies cost reduction as a high-priority technology development need. The recent infusion of private investment into fuel cell development for powering automobiles should help to accelerate the cost reduction of both stationary and mobile units. (Electric and hybrid vehicles are discussed in greater detail in Chapters 3 and 6.)

As these technologies are developed, small-scale distributed generation and storage systems can become valuable new elements of the distributed utility of the future. These distributed resource systems now under development have the potential for creating significant new opportunities:

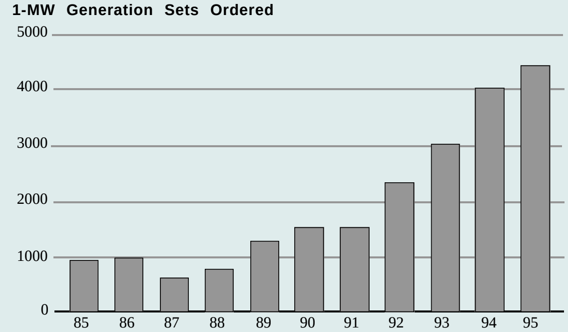
- Higher reliability and power quality
- Higher efficiency, especially in cogeneration configurations
- Flexibility to meet a variety of industrial, commercial, residential, and transportation applications
- Lower-cost service to the end-use customer

Distributed generation and storage technologies will both complement and challenge the existing electricity distribution system.

A related issue is the ongoing convergence of the gas and electricity distribution systems, especially with respect to customers with significant power quality and reliability demands. To the extent that these customers self-generate, they will do so almost exclusively through the gas grid. Analogous to the mainframe and personal computer, the gas-based distributed generation option will complement as well as compete with the existing electricity distribution system, encouraging improved performance and cost of both. Given the rapid rate of technology development, the lack of interconnection standards and certification protocols for distributed power sources is becoming the pacing issue.

By 2003, a new generation of microturbines is expected to be commercially available at sizes down to 10 kW. Fuel cells should also be well-suited for a wide range of distributed applications because they are efficient and clean. Assuming sustained investment, at least

Demand for distributed generation sets is growing rapidly to meet customer requirements for improved reliability and power quality.



Source: Bechtel

20 GW of distributed resources are forecast for installation in the United States during the coming decade alone. This includes a potential U.S. residential market of 25 million households where the gas-electricity cost differential is equivalent to more than $0.05/kWh. Even larger markets exist outside the U.S. where the differentials are relatively higher.

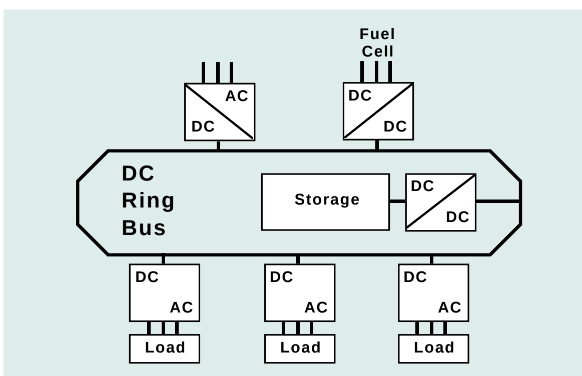
In addition to developing improved hardware, the Roadmap foresees the growing importance of improving tools for understanding and managing the interactions of distributed resources with the existing distribution system, as well as developing control systems for large grids with a mixture of distributed and central generation. In particular, to provide peaking power and premium power support for a distribution system, distributed resources must be dispatchable. This will require adding a variety of remote monitoring, communications, and control functions to the system as a whole. Custom Power controllers are expected to play a major role in performing communications and control functions on the distribution system, in addition to providing power conditioning. Finally, distribution systems with mixed distributed and central assets are likely to require dedicated VAR (volt-ampere reactive) generation for system support and stability. In general, distributed resources will not produce VARs in the quantity or location needed for grid stability. Distribution system operators will need the capability to produce VARs to balance the system, either through the dispatchable "must-run" generators of today or the "silicon VARs" of tomorrow. The latter can be produced by the emerging family of High Power Electronic Controllers (HPEC), which will use FACTS-like devices to inject VARs into the system to stabilize voltage.

DC Microgrids for Distribution Systems

Greater use of direct current has several advantages for distribution networks. DC distribution links, for example, can directly supply power to digital devices on the customer's site, and connect distributed generation systems to the grid without the need for DC/AC converters. They can also increase service reliability by reducing the spread of disturbances from one customer to another and enable each customer facility to operate as independently as desired, using distributed generation and storage. DC cables could also be placed in the same ducts as gas and water pipes because they eliminate the generation of AC-induced currents. Potentially, DC cables would cost less than AC cables of the same power rating because they need less electrical insulation and experience less resistive losses and no dielectric losses.

Up to now, AC/DC converter technology has been too expensive for routine use on utility distribution systems. With the rapid decline in the cost of power electronics, however, such converter technology should become inexpensive enough to facilitate DC distribution systems by about 2005.

Basic DC ring bus system with parallel converters and DC choppers provides superior power quality by isolating customers from system disturbances.



One DC distribution option uses a high-temperature superconducting DC loop bus to integrate bulk power from a transmission network with local distributed resources. Emergence of such a network would require development and widespread use of low-cost DC/AC converter technology to provide power to retail customers. Such superconducting DC loops could provide premium quality power for large urban regions, compared to today's networked distribution systems that serve mainly downtown areas. Technology could enable such DC loops to become a common feature in distribution systems by 2010.

System architectural tools also need to be developed in parallel with the new sources of distributed generation to avoid several threats:

- Disruption and possible fragmentation or stranding of the distribution system
- Excessive infrastructure costs in pursuit of power quality and reliability
- Higher cost to the end-use customer

Some of the key technology targets and corresponding knowledge gaps in the power delivery area are summarized in Table 2-1, along with first-order estimates of their R&D funding requirements over the next 10 years.

Table 2-1 Power Delivery System R&D Funding Requirements				
Targets	**Critical Knowledge Gaps**	**10-Year Funding Outlook ($million/yr)**		
		Current Funding	**Additional Funding Needs**	**Total Funding Needed**
Increased reliability and carrying capacity of the North American transmission grid	• Wide-bandgap semiconductors for FACTS • Satellite-based Wide Area Management Systems (WAMS) • High-performance polymeric and superconducting cables • Streamlined, lower-cost construction techniques for underground transmission • Power flow control in complex grids (hardware, software, communications systems, integration with transaction management functions) • Information technology systems to control the physical grid and manage transactions	100	100	200
Removal of geographic constraints on transmission of power and services	• Removal of transmission bottlenecks among North American regions • Capability for continental-scale power wheeling	100	100	200
Emergence of the distributed utility	• Cost-effective distributed generation and storage technologies • Interconnection standards plus control and protection systems for mixed central/distributed systems • Low-cost converter technology to enable DC distribution networks • VAR support without requiring new generating capacity	200	200	400
Protection against natural and human-caused threats to the electricity infrastructure	• Complex interactive network methodology to understand and manage power system complexities and vulnerabilities • Real-time wide area communications and control systems • Hardware, software, and procedures to prevent cascading failures	*	200	200
Total Funding		**400**	**600**	**1,000**

**Data unavailable*

3 The Customer Challenge

...Adding Value with Intelligent Electron Services

The integration of the power delivery and knowledge networks into a single "intellectric" grid sets the stage for a growing variety of products and services designed around energy, information, and other networked services, and crafted to serve customer needs in a competitive environment. Customers at home will enjoy enhanced ability to manage comfort, security, privacy, entertainment, and education. Business and industrial customers will gain new capabilities for streamlining processes and reducing costs, as well as expanded opportunities for growth, as they in turn offer new services to their customers. Though desirable, this evolution of the current electricity supply system is not inevitable. Realizing the larger economic opportunities offered by an advanced power system will require substantial investments in R&D and system infrastructure.

Customer-Managed Service Networks

On the horizon: customer-managed "virtual utility" services.

The electricity industry is already expanding from its traditional generation, transmission, and distribution dimensions to include energy services, power marketing, and information-technology-based services and products, all geared to provide greater customer value. As customers are provided with greater choices among competing suppliers, the next logical step envisioned by the Roadmap participants is the transformation of power distribution systems into truly customer-managed service networks, delivering an array of intelligent energy services. The networks would be completely flexible, controllable, and configurable, optimized for specific end-use requirements, and automatically self-correcting for disturbances. In effect, they would become "virtual utilities," allowing customers to assemble a portfolio of optional services. Customer performance criteria for such networks were identified by the Roadmap participants to include economic productivity and cost improvement, social equity, environmental stewardship, quality of life improvement, and sustainability.

The transformation would enable an electricity enterprise to provide universal access to:

- Complete, real-time information facilitating customer choice
- 100% reliable, distortion-free power quality
- At least doubled systemwide energy efficiency
- The least polluting energy available
- Lower energy cost and higher value of service
- Other benefits arising from competition between distributed generation and grid-based innovation to meet rising customer performance expectations

To the extent the customer-managed "virtual utility" service concept pervades the economy, it will become an important conduit for introducing innovative technologies both upstream and downstream of the meter. It could increase energy efficiency throughout by linking the larger systemwide intelligence with that embedded in customer sites.

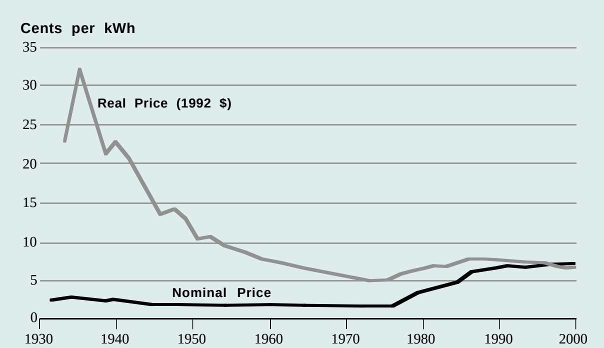
The electricity industry is in many ways returning to its roots. Thomas Edison invented not just electric light, but rather the concept of electrification. The first electricity supply system was, in a sense, viewed as an engineering detail required to sell the service of illumination. Within a decade, however, electricity itself became the product, spawning today's power industry. But even this was not the greatest result of Edison's innovation. Rather, the unique capacity of electrification to improve human life has become Edison's legacy for the 21st century.

Moving Beyond Electricity as a Commodity Energy Form

The transformation to an interactive, customer-managed service network will continue to move the business dynamic of the electricity enterprise well beyond offering electricity as a commodity. This is in keeping with the shift in business toward rendering services of far greater value than the original input commodity. DuPont, for example, is now delivering to automakers the service of painting cars, not gallons of paint. This puts them inside the factory, working with the auto company to improve the quality and cost of car painting. It shifts the work to the supplier, and may actually shift the financial incentive of the supplier toward selling less paint rather than more. Likewise, energy suppliers could provide a much broader range of services that enable customers to save energy—and be compensated on the basis of actual savings realized.

Such a focus on value-added energy services is in line with customer expectations. Energy users are likely to have less and less affinity for molecules or electrons, and greater and greater affinity for the services they render. This implies a growing need for the providers of energy commodities, and the owners of gas and electric grids, to involve themselves in differentiating and building end-use service value in order to protect their supporting businesses.

Electricity prices, in real terms, declined steadily until the 1970s, when supply interruptions, environmental costs, and inflation interceded. Technology should allow the historic trend to resume in the future.



Source: Cambridge Energy Research Associates

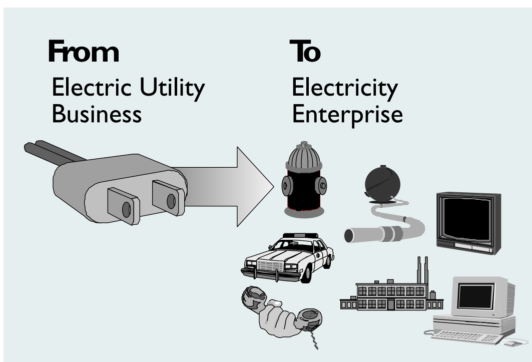
Over the last 25 years, U.S. bulk electricity consumption has grown in close proportion to U.S. GDP growth (~70 billion kWh/year). In future decades, however, increases in the efficiency of electricity end uses, augmented by expansion of the customer-managed digital economy, could actually slow growth in bulk electricity consumption, even as electricity becomes an ever-greater fraction of total energy end use.

The movement to electricity as a service has still another dimension. The overlap of network applications in the control, accounting, and customer relations activities associated with infrastructure services in telecommunications, gas, water, and waste disposal could lead to greater integration of infrastructure management. This could yield major savings for society through both economies of scale and system streamlining. And it might be a viable opportunity to serve the growing mega-cities of the world, which must build an infrastructure from the ground up at the lowest cost possible. As a result, efforts to achieve horizontal integration of utility functions are likely to accelerate.

Failure to pursue this path carries some large opportunity costs:

- Decreased value of deregulation
- Higher infrastructure costs, as utility service integration is slowed or stopped
- Lost business opportunities

Restructuring has opened the electricity enterprise to new services and new players.



Technologies for Customer-Managed Service Networks

The potential of a full-featured customer service network is relatively easy to imagine. However, the technologies needed for the transition are evolving and the pathway to reach such a network is still unclear. For example, providing multiple utility services—including electricity, gas, telecom, Internet access, cable TV, and water—requires new customer interface technology. Low-cost electronic meters with two-way communications capability are needed to provide real-time pricing (RTP) options, which will be the cornerstone of a competitive retail market. Even more sophisticated interface technologies will be required to facilitate combined utility services, such as electricity and telecom, that depend on high-bandwidth communications links. To meet customer needs, meters will need to be able to distinguish multiple suppliers of multiple services, and be transformed into gateways for service innovation.

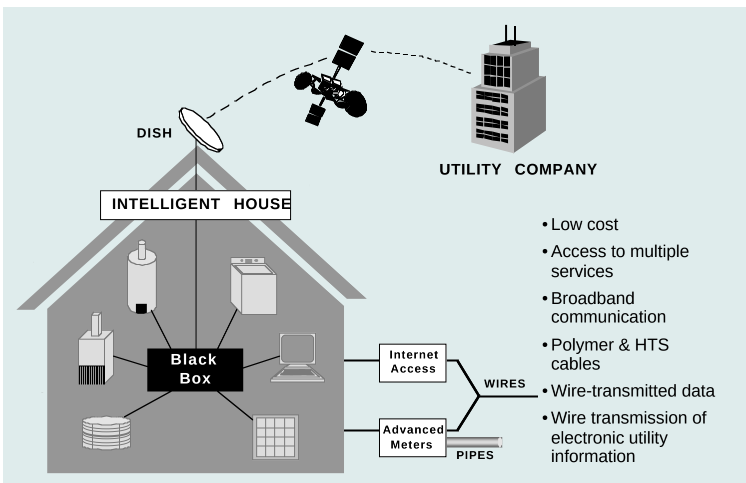
Customer interface development is a rapidly expanding field, with many potential new players including Internet-based service providers. Utility demonstrations of modular electronic meters in the context of automatic meter reading (AMR) are already in progress. Meters capable of offering differentiated electricity service—including power quality monitoring—are expected on the market by 2001. "Virtual meters" capable of

Meters capable of offering differentiated electricity service—including power quality monitoring—are expected on the market by 2001.

providing integrated billing for multiple utility services could be broadly available soon thereafter—perhaps in the form of an energy network computer that monitors the services and delivers a variety of information to consumers. Development of new sensors for monitoring energy consumption and other functions will likely help reduce the cost of advanced metering. Sun Microsystems, for example, has recently unveiled its Jini Technology, which provides communication links among a large class of customer equipment, and announced that 27 manufacturers will add the necessary microprocessor to their products to allow connection via Jini Technology.

New standards for integrated communications and control will be needed to expedite data exchange and real-time operational management throughout a more decentralized and complex distribution system. The technical basis for such integration can be provided by the Utility Communications Architecture (UCA), which specifies open-systems protocols and standards for linking hardware and software from different vendors.

Increased access to electronics and telecom advances will drive a revolution in utility services.



Handling the data gathered from these advanced smart meters and other sources for purposes of pricing and billing promises to be a major challenge. Needed tasks include restructuring of customer information systems to provide greater flexibility in changing the products and services offered to customers and data consolidation for load profiling. In the U.K., the cost of just the data processing systems needed to support load profiling for the mass market is expected to reach nearly $50 million. The cost in the United States would be proportionately higher.

The customer information base will become an important and increasingly valuable asset.

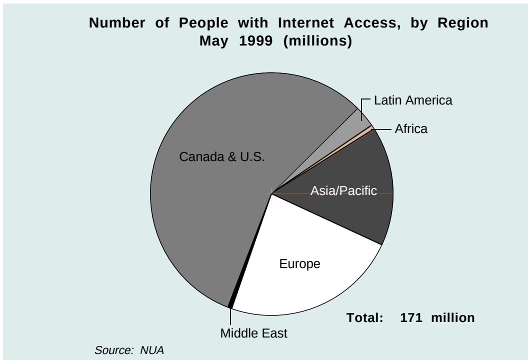
With smart meters and real-time information, energy companies could shift from load profiling to real-time metering and data analysis. The resulting higher-quality data could be used to project future system conditions, make better deals with suppliers, or to identify attractive or complementary loads. Consequently, the customer information base will become an important and increasingly valuable asset, fostering major investments in these databases to provide them with a modular architecture and make them easy to manipulate quickly. Modular billing systems should be commercially available by 2003.

However, this vision can easily be shortchanged without a sufficient infusion of R&D funds to bring down the cost and increase the capability of interactive metering. Even then, the new meter will be of marginal benefit if there are no new services to be delivered, and new services can't or won't emerge until the market density of meters can justify them. Several issues must be addressed to remove the obstacles:

- To jump-start the residential market, service providers may have to subsidize advanced meters in the home until the services expand beyond the management of energy to the robust management of comfort, convenience, security, privacy, entertainment, education, and caretaking.
- Intelligence about customers will be a prized asset, and ownership issues surrounding customer data will be debated among providers, customers, and regulators alike. The value of privacy will be a growing challenge, but will also offer new business opportunities, such as customer-managed data services.
- Distributed power generation advances, including fuel cells, are becoming available at the small commercial and residential level. With further development, these could become the power supply equivalent of personal computers and cell phones. This will provide vigorous competition, encouraging corresponding service performance improvements.

The strategic advantages of the new intelligent services and the new integrated power and communication network will likely first become evident in industrial and commercial

Over 170 million people have gained Internet access, most in the last three years in the U.S. and Canada. Explosive growth rates are expected to continue as commerce and customer services acquire electronic dimensions.



environments, followed by the residential market. These sectors will become the vehicles for delivering not only new and better services to the customer, but also for delivering innovation, productivity, and efficiency from business to business.

The Roadmap participants also expect that the integration of multiple utility services will be accompanied by increased pressure to place the required infrastructures underground. Increased use of superconducting distribution cables and DC rings, discussed in Chapter 2, will enable this trend. Improved underground construction methods will make buried utility facilities more attractive for distribution systems. In the short term, guided boring technology and micro-tunneling will rapidly lead to productivity improvement in underground facility construction. By about 2005, construction rates of 400–500 feet per day should be achieved in constructing a 6-foot-diameter integrated "utility corridor" for electricity, communications, and other services. Standardization of underground designs and expanded use of robots would further reduce construction costs.

Transportation and Electricity

An additional dimension of customer-managed service networks is the convergence of transportation and electricity, which is covered in more detail in Chapter 6. In the context of network services, personal electric vehicles may play a new role in the creation of the distributed utility. Several concepts for advanced vehicles are under development, differing primarily in the choice of motive power (battery, internal combustion engine, or fuel cell to drive an electric motor/generator) and in the amount of battery power available to store energy on board and to supplement the motor. One design of particular interest uses a proton exchange membrane fuel cell (PEMFC). The PEMFC configuration consists of gas diffusion electrodes containing an active catalyst layer separated by an ion-conducting polymer membrane. It operates at about the boiling temperature of water—too low for cogeneration purposes but ideal for use with water and space heaters. Lightweight and small, the PEMFC is an ideal candidate for residential and vehicle use, with most current development efforts concentrated on products in the 3–250 kW range.

More than a dozen major firms worldwide, including GM, Daimler-Benz/Chrysler, and Toyota, are currently developing fuel cell technology for cars. Most designs incorporate an efficient (40%), 50–100 kW PEMFC, a size range that is also attractive for stationary distributed resource (DR) applications. Achieving automotive cost and performance targets will ensure that, even with the engineering needed to extend lifetimes, stationary fuel cells will cost well below $500–700/kW. At this price, stationary fuel cells could see widespread use in commercial buildings and other DR applications.

The inherently underutilized storage and power generation capacities of new hybrid electric vehicles could be connected to serve residential and commercial building loads.

Once fuel cell or hybrid electric vehicles are in common use, they could be connected to residential and commercial building loads or local distribution networks. During the majority of time when vehicles are not being operated, they could provide an extensive distributed power generation and storage network. If, for example, 1 million such vehicles were on the road in the year 2010, they could contribute 50–100 GW of generating capacity, or about 5–10% of anticipated U.S. capacity. The wide-scale availability of interactive communications, described above, coupled with power electronics, will allow for the required remote control and management of highly complex networks capable of incorporating a large and variable contribution to distribution systems.

Some of the key technology targets and corresponding knowledge gaps related to customer-managed service networks are summarized in Table 3-1, along with first-order estimates of R&D funding requirements over the next 10 years.

Table 3-1 Customer-Defined Service Networks R&D Needs				
Targets	**Critical Knowledge Gaps**	**10-Year Funding Outlook ($ million/yr)**		
		Current Funding	**Incremental Future Funding Needs**	**Total Funding Needed**
Premium power for a digital society	• Advanced power electronic controllers (custom power devices and software) for the distribution system • Fully automated distribution system • Integration of premium power quality industrial parks	100	100	200
Integrated utility services (electricity, gas, telecom, information, water, etc.)	• Interactive meters, smart appliances, communication systems, billing and pricing systems, and standards for multiple-utility services • Underground common service corridors for all utilities • Customer access to complete real-time market information • Customer-defined service network capability	200	300	500
Integration of transportation with the energy delivery network	• Interfacing of fuel cell–powered vehicles with the distribution grid; infrastructures to allow autos to deliver electricity to, or receive it from, the grid	<100	100	200
Total Funding		**400**	**500**	**900**

4 The Economic Challenge

...Assuring Economic Prosperity and Leadership

The U.S. shares with many other developed countries the quandaries of generally slow productivity growth, wage stagnation, growing economic and social disparity, rising environmental expense, and the prospects of soaring costs to meet the needs of an aging population. Financial resources will likely be stretched to the maximum, and competition for scarce resources will come from all directions. This economic challenge will place increasing pressure on technology innovation to create the productivity advances and wealth needed to address these issues. Technology can meet this challenge, but only if it advances on a broad front and at a pace that is sufficiently vigorous and continuous to stay ahead of the accelerating social and environmental problems.

Technology's Role in the Global Economy

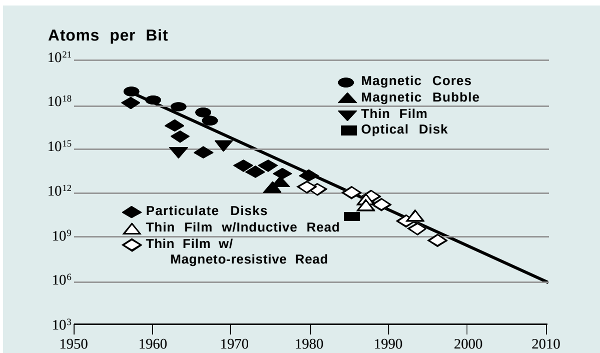
Technology innovation now accounts for more than 50% of the economic growth in the U.S. and other developed nations. The Roadmap participants expect the historical ascent of technology as a driving force in the global economy to continue unabated in the next century. The developing nations have also recognized this fact, and many have established technology-based growth strategies to compete in the global economy with the advantage of a much lower wage structure.

Some technology trends are favorable to the newly emerging economies of Asia, Africa, and Latin America. For one, the entry barriers to business and industry are being lowered as the capital intensity of new knowledge-based industries continues to decline. Moreover, as both capital and technology become more mobile on a global scale, economic enterprises will be seeking other factors of competitive advantage around the world, including cheaper labor. The result is likely to facilitate broad-based economic progress around the world, which, as discussed in Chapter 6, will be the essential underpinning for a sustainable future. However, this will place new competitive pressure on the U.S. economy. As a high-wage nation, the U.S. must increasingly depend upon technical creativity and innovation, as well as on a superior infrastructure, to maintain its competitive position. Gregory Tassey of NIST points out that especially in a mobile global economy,

> *The major factor distinguishing one investment environment from another is the subset of economic assets that are relatively immobile. Such immobility confers competitive advantage which is not easily undone. For the most part, these assets and their sources constitute the infrastructure of a modern domestic economy. More and more of this infrastructure is technology-based. However, infrastructure by its nature is subject to persistent under-investment by the private sector.*

The U.S. will need to come to grips with this investment challenge, because the economic dangers of under-investment in infrastructure will be greatly magnified by global competition in the new century. Failure to transform the electricity infrastructure to anticipate the industries of the future would have serious economic and social repercussions.

Technology advances enable tighter and tighter packing of information.



Source: Paul M. Horn, Research-Technology Management, 1999

Building the Infratechnologies of the Future

Over 25 billion microchips are in service today worldwide and most information is generated, transmitted, and analyzed by some form of microprocessor-based equipment. Today, the world is undergoing a new wave of economic expansion based upon the fusion of digital microprocessors, electrotechnologies, information technology, and telecommunications, all increasingly networked on a digital platform. As the wave gathers momentum, the microprocessor is expected to increase in power and decrease in size and cost to the point that it will become truly ubiquitous throughout society. For example, according to Nobel Prize winner and Lucent Technology Vice President Arno Penzias,

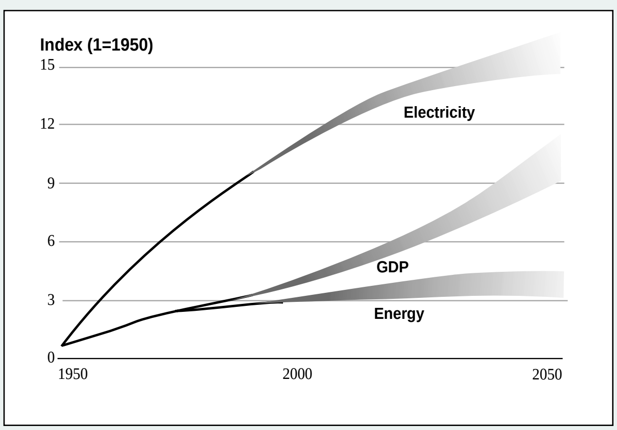
The Economic Connection

Historically, economic growth has been highly correlated with electricity use. But is electricity use a contributing cause of economic growth, or a result? And if electricity use does influence economic growth, in what ways is this effect created? Will it continue in the future? Though elusive, the answers seem to lie in the well-documented causal connection between technical innovation and economic growth—and incorporating electricity's essential role in that innovation.

Decades of academic studies indicate that new knowledge and innovation, or what Nobel Laureate Robert Solow describes as "technical change," is likely to account for 80–90% of total factor productivity growth. In turn, productivity growth is estimated to account for more than half of GDP growth. Consistent with these results, Boskin and Lau (1992) found that in the period 1948–1985, "technical progress accounted for half or more of an industrialized nation's economic growth."

This technical progress is especially dependent on electricity-based innovation, which can create opportunities for productivity growth in two ways: developing improved electric end-use electrotechnologies and improving the value-producing capabilities of the electricity infrastructure itself. Both increasingly arise from innovations in basic areas such as materials, sensors, information technology, and model-based systems. As these permit breakthroughs in infrastructure and end-use applications, progress accelerates toward higher efficiency, economy, capability, and value.

Comparative Growth in U.S. GDP, Energy and Electricity



What about the future? Electricity has a unique ability to convey both energy and information to yield more precise, efficient, and higher-value applications. Such uses of electricity will be increasingly dominant in the 21st century, as electrically driven and controlled processes and devices of all kinds become ever more sophisticated and information-rich. For this reason, electricity seems destined to claim an ever-increasing share of total energy use, continuing its historical trend. This "electricity fraction" grew from 10% in 1940 to 25% in 1970 and 38% today—and this trend could lead to electricity reaching two-thirds of total U.S. energy use by 2050. But as its share grows, electricity's inherent precision and economy will contribute to a continued decline in total energy use intensity—conserving energy resources, reducing pollution, and enhancing productivity. Future electricity-based innovations are therefore expected to make even greater contributions to technological progress, productivity, and economic growth.

We can look forward to a millionfold increase in the power of microelectronics in the next few decades. Such advances should yield low-end computers more powerful than today's workstations, for about the price of a postage stamp and in postage stamp quantities. There will be no keyboards or large displays at those prices, but they will recognize speech and connect to networked resources for whatever help their assigned tasks call for.

The advent of an intellectric age carries profound implications.

Microprocessors, electricity, telecommunications, and information will all become imbedded elements of the new infrastructure needed to stimulate, renew, and support future patterns of productivity growth. The implications of this new intellectric environment will be profound:

- **It changes everything about what constitutes adequate electric service**. Perfect power becomes necessary as the digital circuitry at the heart of industrial and commercial operations becomes more precise and more sensitive to even minor power perturbations. The concept of quality is becoming increasingly challenging as the power system and the economy it serves becomes more complex and diverse. This is the nature of system development (e.g., Ilya Pirgogine, *Order Out of Chaos*).
- **It changes the way work can be organized and carried out**. Instant access to knowledge bases, rapid and massive data processing, and modeling and simulation advances will add fundamental new sources of productivity to the work and learning environment. The wide communications bandwidth of fiber optics plus the emergence of spectral multiplexing will likely cause the bottom to drop out of telecommunications costs within a decade. This will in turn lead to greater decentralization of work, from roughly 5% of the workforce today to 20% by 2010, and cause a ripple effect on transportation.
- **It changes the way problems can be dealt with**. Jobs can be created at a distance and transported into inner cities and rural areas. Environmental responses can be organized and coordinated on a global scale. Waste and pollution can be minimized through industrial-ecologically modeled webs, where the waste from one process becomes the feedstock for the next. With ecological principles, "the focus changes from merely minimizing waste from a particular process or facility, commonly known as pollution prevention, to minimizing waste product by the larger system as a whole" (Richards, Allenby, Frosch, 1994). These advances allow us to think in terms that emphasize products

designed for recycling and the conversion of waste streams into valuable by-products. Industrial ecology principles can minimize total resource consumption, including energy use. Ideally, every output of manufacturing is returned to the ecosystem or recycled for future production. In the long term, this may be both our principal technological challenge and our greatest opportunity. Such complex ecologically modeled systems, which depend upon collaboration to use resources in the most efficient manner, are better equipped to dynamically respond and adapt to external forces of change.

In the long run, industrial ecology may be both our principal technological challenge and our greatest opportunity.

The digital technological transformation now underway represents the third fundamental industrial and commercial transformation of the last 125 years. The first was the emergence of mass production in the 19th century; and the second, the manufacturing technology revolution spawned by World War II. Each of these transformations has been characterized by increasing levels of high aggregate economic growth and redistribution of wealth among corporations, industries and nations. Each has depended on public/private investment and an increasingly complex and sophisticated technical infrastructure, as well as on new development and commercialization processes. As in the past, the corporations, industries, and nations that are most effective in exploiting this latest transformation will become the economic winners.

Focusing on the Enabling Technology Platforms

To maximize the economic value of the ongoing digital revolution, and to ensure that the new intellectric environment can achieve its full potential in supporting future productivity growth, investments will have to be stepped up in critical areas of technology. Roadmap participants singled out five especially important limit-breaking "technology platforms" where acceleration of the underlying sciences would have large-scale impact, not only on enhancing the capability of the infrastructure, but on improving productivity in a wide range of critical manufacturing and process industries in the first quarter of the new century. The four platforms are:

- **Materials:** New advanced materials, polymers, composites, and special structures engineered one atom at a time will enable electrotechnologies to be more productive and energy efficient, and create new products and systems (mechanical, chemical, electronic, optical) with higher performance capabilities, greater adaptability, and reduced environmental degradation. They will be used throughout the production, conversion, delivery, and use of energy.

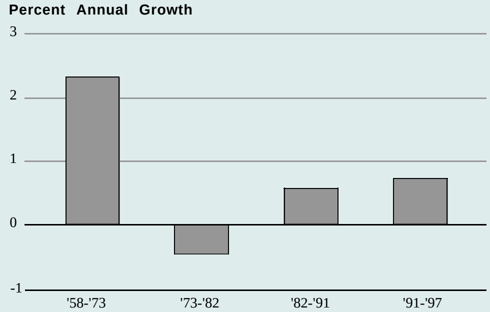
- **Sensors:** New sensors now being developed will provide real-time feedback to optimize the operation and control of electrotechnologies. They will be smaller, more accurate, better able to withstand harsh environments, and in many cases, integral to the system they are monitoring.
- **Microminiaturization:** Machines and tools that can be fabricated from silicon at a scale from a few microns to hundreds of microns could perform specialized tasks. Nanotechnologies can improve process speeds, quicken development cycles of new products, and allow mass production of machines that perform tasks in entirely new ways (e.g., robots that deliver drugs to precise areas of the body) or at a different scale (e.g., nano-scale combustion turbines the size of shirt buttons, generating 20 watts of electricity). Nanotechnology will also allow the integration of microsensors into structures and process equipment, thus forming the basis for smart materials whose properties change in response to the operating environment and smart systems that can adapt to their environment to ensure optimal performance.
- **Information technology:** Similar advances are occurring in the broad area of information processing and modeling. Complex adaptive systems technology, for example, can be used to simulate the operations of the power grid, and to design and operate the grid of the future. This technology is also being applied broadly in communications, military operations, and other complex processes. The power industry is in an excellent position to both learn from, and contribute to, the state of the art in this field.
- **Biotechnology:** Advances in biotechnology over the next few years will lead to deciphering of the human genome as well as cracking the genetic code for many other living species. These advances will open the door to new approaches for disease treatment, pharmaceutical design and manufacturing, and genetically engineered agricultural systems. Spinoffs of this work will lead to biological computers and advances in biomimesis—the application of the physical and chemical processes used by living systems to improve the performance of systems and structures in the non-living world. Examples of biomimesis include artificial photosynthesis, high-strength/high-toughness ceramic composites, and novel carbon sequestration processes. These and other new

developments in the biological sciences will be employed to boost economic growth and productivity, address the energy/carbon conflict, and implement the principles of global sustainable development.

Recent developments underscore the large potential these platforms hold for enhancing the capability of tomorrow's infrastructure. New ceramic oxides, for example, have provided the foundation for the wireless telecommunications now sweeping the globe, while still other ceramic compounds have opened the door to practical superconducting transmission and storage in the next few decades. Advances in carbon fullerene materials may lead to materials and systems with ultra-high electrical conductivity, high strength-to-weight ratios (100 times the strength of steel at 1/6 the weight), and high resistance to corrosion. The same class of materials could be manufactured to have semiconducting behavior, excellent light-gathering behavior, and other properties that will be useful in a variety of industrial applications, as well as in electrical conduction. Despite intense research, global production to date is only a few grams. Achieving the potential payoff to industries as wide-ranging as aerospace, computers, and energy will require a major R&D effort over the next decade.

Further improvements in capability and productivity can be achieved by combining the attributes of two or more of the platforms. For example, advanced materials and structures with on-board sensors, machine intelligence, and active controls can lead to smart products with the inherent ability to change shape, viscosity, and physical and mechanical properties in response to external stimuli. Similarly, smart sensors, often at nanotechnology scale, can unobtrusively monitor and control the workplace with attendant improvement of energy and resource efficiency and human productivity.

U.S. Total Factor Productivity growth rates (based on the combined inputs from labor, capital, and technical innovation) remain inadequate for long-term prosperity.

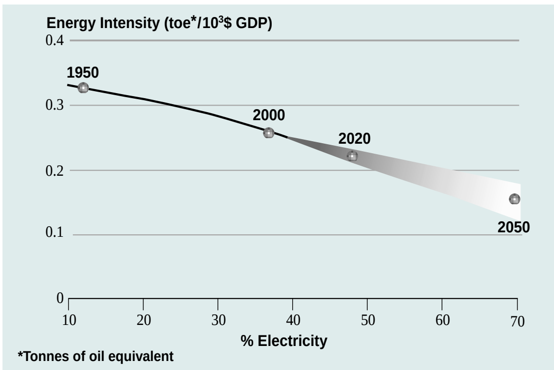


Source: Bureau of Labor Statistics

Additional Productivity-Enhancing Opportunities

Some high-impact future electrotechnologies linked to the platforms include plasmas, lasers, and electron beams for materials processing; electrochemical synthesis; biotechnology; biomimetics; high-temperature superconductivity; and adaptive, digitally controlled electric processes. Future facilities using these advanced electrotechnologies can be operated in new ways to simultaneously optimize productivity, energy use, materials consumption, and plant emissions.

Electrification will continue to improve global energy efficiency.



Their impact is not yet known, but it could be analogous to the dramatic change in the U.S. steel industry caused by the growth in electric arc steelmaking over the last 30 years. Comparison of the electric arc furnace with the basic-oxygen furnace shows energy needs dropping from 9.4 GJ/metric ton to 5.7 GJ/metric ton of steel. And by using scrap metal as the feedstock, the electric arc process saves the energy originally used to refine the steel. As a result, electric steelmaking has captured nearly 40% of U.S. steel production and given rebirth to a globally competitive industry. Electrification has also opened the door to subsequent efficiency improvements. For example, with advanced power generation (e.g., combined-cycle units), the primary energy requirements could be cut again, to around 3 GJ/metric ton. In addition, future improvements in electronic process controls will likely increase throughput, energy efficiency, and quality control.

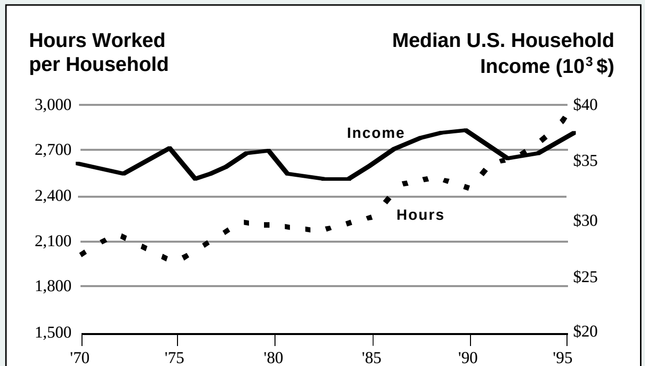
Setting Stretch Goals for the Economy

Economic growth and productivity have received strong boosts in the past from both short- and long-term investments in R&D. With sufficient investment in research, new and emerging electricity-based technologies could accelerate this trend through 2020 and beyond, revolutionizing manufacturing, as well as many service industries. The Roadmap participants believe the growing potential of electrotechnology-based innovation should be used to set some major stretch goals for the U.S. economy. By 2020, there is a distinct possibility of:

The Real Issue of U.S. Productivity

The issue of U.S. productivity and economic prosperity is about more than our place in a competitive world. What hangs in the balance is the ability of the U.S. to sustain its security, standard of living, and social stability. More and more products and services are vulnerable to being shifted elsewhere unless their productivity justifies the higher American wage structure. Although the U.S. economy continues to grow, the contribution from productivity improvements is insufficient to meet these challenges.

Working Harder to Stay Even



Source: Bureau of Labor Statistics, Census Bureau

- From 1950–1970, as a result of rapid productivity improvements, U.S. average hourly wages in constant dollars increased by 50%, and the GDP doubled, while the fraction of the population employed in the work force remained nearly constant at about 27%.
- In contrast, from 1970–1990, productivity stagnated and average hourly wages in constant dollars actually declined by 7%. The GDP grew, but primarily because the fraction of the population employed nearly doubled.
- From 1990–1997, U.S. total factor productivity growth rose at a rate of just 0.8% per year. But essentially, all this growth was concentrated in the information technology (IT) producing industries that accounted for less than 8% of U.S. GDP. Further, these industries brought down overall inflation by an average 0.7 percent.
- During the 1990s, although profits have increased, average dollar earnings have continued to stagnate and the fraction of the population employed in the work force is reaching saturation at around 50%. U.S. economic expansion in the last decade has become more dependent upon shorter-term, expedient pathways: reducing the budget deficit and corporate restructuring for efficiency, for example. While this has produced significant short-term economic gains, the productivity fundamentals will challenge the sustainability of these gains unless the atypical productivity growth now seen in industries such as information technology can be more broadly realized.
- Looking to the coming decades, the opportunities for significant work force expansion are limited. Today, the U.S. has the largest proportion of its population in their prime working years in history. After 2010, however, the proportion of workers to elderly people will shrink rapidly as the elderly population grows. This means that real economic growth must depend once again upon fundamental improvements in productivity. In short, the focus must be on building economic muscle, not just reducing fat. The alternative will be an increasingly unsupportable economic burden on working-age people.
- Without substantially higher productivity growth rates, U.S. wages, investment margins, and responses to social needs will be increasingly difficult to sustain in ever more competitive world markets. If the U.S. is to meet the challenge, then it must remain the leader of innovation.

• Doubling the growth rate of total factor productivity

• Cutting energy intensity in half

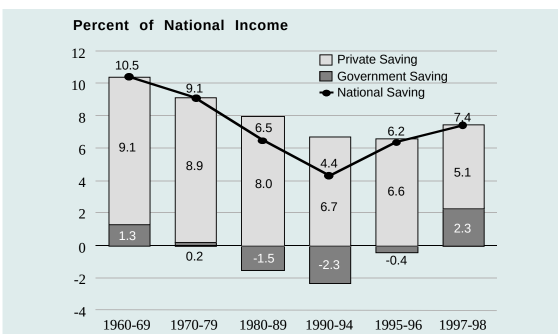
• Eliminating most waste streams

• Adding a net trillion dollars to the U.S. GDP

Achieving these goals will require highly efficient enterprises—factories and their counterparts in the service sector that learn from experience. With self-adapting processes, they can redesign and change products/services on demand, minimize waste, self-diagnose and self-repair, and specify or create the most effective mix of raw materials, including energy.

Failure to pursue such opportunities through aggressive and timely R&D investment would likely impose a number of losses, including U.S. technical leadership in areas essential to future competition in the global economy.

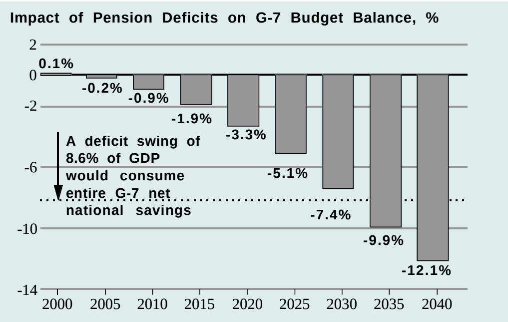
While U.S. private saving continues to decline, government saving is increasing after a prolonged period of deficits, allowing net national saving to rebound moderately.



Source: Committee for Economic Development

Globalization creates a series of imperatives for the U.S. and other industrialized nations if they are to maintain their prosperity in the coming decades. High and rising wages cannot be justified unless new products, services, and processes are continually created. Lower-skilled workers are increasingly vulnerable because they must compete with other lower-skilled workers around the world for jobs and wages. Globalization is leveling the innovation playing field and collapsing the margins of technological leadership. At the same time, the pressure on productivity and wage growth will increase rapidly in the coming decades as the population of the U.S. and other developed nations ages rapidly, leaving fewer people of working age to support growing social costs. By 2030, these costs in the U.S. would require an amount equivalent to doubling the personal income tax. Roadmap participants question the preparedness of the U.S. for success in a world with a much broader capacity to innovate.

Unless productivity growth rates increase, widening public pension deficits could consume the total economic savings of today's industrialized (G-7) nations.



Source: Peterson, Peter G. in Foreign Affairs

Investment in Innovation

The principal obstacle to productivity growth in the U.S. is systemic under-investment in the basics of innovation—infrastructure, education, and research. Public investment in these three areas, for example, has fallen from around 25% of non-defense expenditures in 1965 to 12% in 1995. Relatively few industries in the U.S. have the high R&D-to-sales ratios (8–12%) that seem necessary to sustain world class innovation. These industries together account for only about 7% of GDP. Moreover, increasing technological complexity is creating mismatches between existing corporate strategies and R&D on the one hand, and market opportunities for emerging technologies on the other.

The national platform for innovation is one of the nation's most valuable and least understood natural assets. It is the principal driver for long-term U.S. competitiveness as measured by success in the global marketplace and therefore must not be allowed to erode. As noted by Debra Van Opstal, Vice President of the Council on Competitiveness,

> *Once lost, innovative leadership will not be readily or inexpensively recaptured, if it can be recaptured at all.*

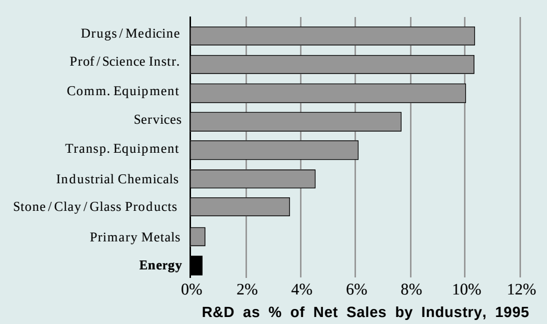
The national capacity for innovation hinges on a complex integration of resource commitments, institutional interactions, national policies, and investment market access. Although regulatory and legal frameworks are critical elements in cost and time to market, regulations are rarely assessed in terms of their impact on innovation. In the U.S., many areas of regulation continue to be geared to a bygone era of slower technological change and unlimited domestic markets.

Following are recommendations emerging from the Roadmap dialogue:

- The U.S. must recognize that investments in the basics of innovation require the combined support of both the public and private sectors.

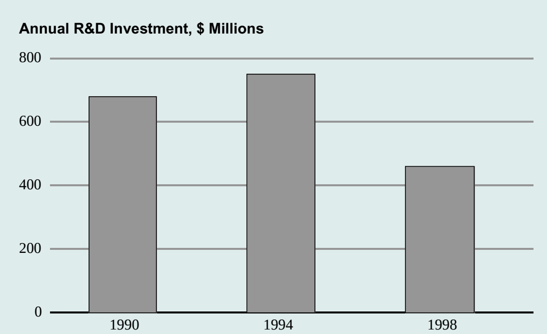
- Disincentives to collaborative R&D should be eliminated at interstate, regional, federal/state, public/private, and U.S./international levels. Currently, growing R&D fragmentation is leading to diminished results and wasted resources.
- A catalyst is needed for R&D collaboration in new forms and at different levels. This ongoing Roadmap process can be a pilot to explore various possibilities. Ultimately, a new set of formal incentives for collaboration will be needed to create the technology tools for global competitive advantage.
- A full range of innovation stimuli need to be explored, including creating tax credits to spur private R&D; increasing federal investment in frontier research; enhancing education; expanding industry, university, and government collaboration; and more secure protection of intellectual property.
- Research funding should be stepped up by at least a factor of three in key technology platforms for innovation (e.g., materials, sensors, microminiaturization, and information) that can boost productivity across a spectrum of industries.

The energy industry invests less than 0.5% of sales in R&D.



Source: Margolis and Kammen

Utility R&D investment peaked in 1994 and is trending downward.



Building Recommitment to Energy R&D

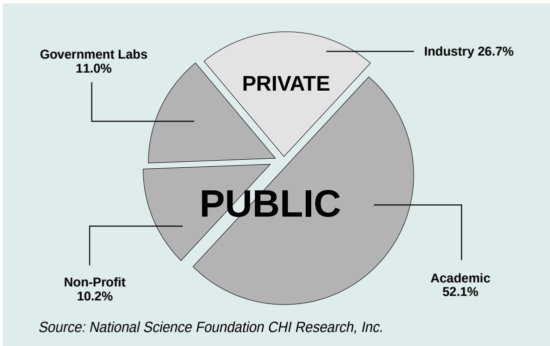
One reason for reduced R&D expenditures in the energy field is that the underlying technologies are mixed economic assets, embracing both infrastructure and private production, and creating both private and public benefit. The utility restructuring transition is exacerbating the situation. Individual firms being transformed from regulated monopolies to competitive corporations find it difficult to justify basic and longer-term R&D. Moreover, U.S. federal energy R&D funding is also at its lowest level in 30 years, relative to GDP. Reasons for the broad decline in federal energy R&D support include the availability of cheap energy, governmental budget constraints, and competing energy constituencies whose advocacy arguments tend to cancel each other out. At the same time, state and local programs to compensate for these deficiencies and to address R&D needs specific to their constituencies tend to reduce the incentives for broader collaboration on issues of strategic national and international importance.

The situation has been summarized well by Robert Margolis and Daniel Kammen, who have recently analyzed the impact of reductions in U.S. energy R&D investment:

> *The U.S. significantly under-invests in energy technology R&D. This under-investment, in an area at the heart of the environmental-economic nexus, is detrimental for both long-term U.S. energy security and for global environmental sustainability. In particular, since the U.S. path is intimately tied to the evolution of global energy systems, this under-investment in energy technologies is likely to reduce the options available in the future to the global community to address the environmental impacts of energy production and greenhouse gas emissions. Ultimately, meeting the challenges will require increasing both U.S. and international energy technology R&D.*

Roadmap participants anticipated the shifting relationships among energy companies, governments, and international institutions during the first 20 years of the new century. In a global market economy, business will be expected to play a larger leadership role in energy policy development and implementation. In turn, government, regulatory, and international institutions will need to focus on providing supporting guidance and incentives for removing barriers, as well as policy integration that spans both the developed and developing regions of the world. On both environmental and energy policy issues, the business community will also be expected to respond with greater leadership in generating workable solutions. Organizations that help energy-related businesses anticipate the future, manage valuable information in real time, and construct credible solutions were seen by the Roadmap participants as filling an essential need, and should receive strengthened support.

75% of U.S. patents emanate from public funding.



Investing in People: Their Education and Training

Prospering in the price-competitive, global economy will require investment in the largest competitive asset remaining to the developed nations—educated people. The U.S. in particular now commands a competitive differentiating advantage in its technical creativity and innovation, but sustained leadership in the coming century will require substantial investments in human resources and the infrastructure of opportunity—educational and research institutions, as well as the technology-based infrastructure upon which their innovations depend. The participants in the Roadmap workshops repeatedly called attention to the need for improved education and worker training at all levels, and for basic scientific research and technology development programs to fuel the innovations essential to global leadership.

The best hope for achieving this future is to ensure that the educational framework for innovation is strengthened and made universally accessible. The Roadmap participants concluded that the nation and the world are at a major turning point in education through the Internet and its successors. The end point is not in sight, but educational networks hold out the promise of nearly universal access by each and every person to the world's institutions, talent, and knowledge; to the establishment of informal global classrooms; and from the vantage point of today, to nearly limitless economic opportunity. As this new talent pours forth into the world's economic mainstream, the pace of innovation is expected to quicken, leading to new markets, products, services, and industries at unprecedented levels of energy and resource efficiency, making the pathway to global sustainability feasible. This is the best hope for dealing with the demographic challenges of the new century. Electricity is an essential enabling agent in making this hope a reality, by providing both the most efficient energy infrastructure and the innovative capabilities upon which future economic growth and quality of life depend.

Some of the key technology targets and corresponding knowledge gaps in the area of economic and productivity growth are summarized in Table 4-1, along with first-order estimates of R&D funding requirements for the next 10 years.

Table 4-1 Economic Growth and Productivity R&D Funding Requirements

Targets	Critical Knowledge Gaps	10-Year Funding Outlook ($millions/yr)		
		Current Funding	Incremental Future Funding	Total Funding Needed
Double total factor productivity growth rates through increased application of electricity-based end-use technologies	• Efficient, low-cost end-use electrotechnologies for application in the process, manufacturing, and service sectors	100	500	600
Accelerate development and application of new technology platforms to support innovation and improve customers' productivity	• Materials, sensors and controls, and information technology advances to improve reliability and quality of electricity-based services—drawing upon uses of these technologies in other industries where possible	100	300	400
Reduce industrial, commercial, and residential energy intensity by 50% through innovative electrotechnologies	• Increased use of electricity to reduce overall energy consumption • Development and optimization of new industrial and manufacturing processes based on electricity innovation • End-use energy efficiency improvements for buildings, transportation, and industry	400	600	1,000
Eliminate waste streams and achieve near-zero emissions from the energy sector	• Integration of energy utilization into recycling and industrial ecology programs	100	100	200
Total Funding		**700**	**1,500**	**2,200**

5 The Energy/Carbon Challenge

...Managing the Climate Change Issue

What will the energy requirements be for our expanding world? As a result of population growth and needed economic expansion, the scenarios of WEC and others indicate that the world will require 50–100% more energy in 2050 than it does today. These scenarios also show that electricity use is expected to grow even faster as the world demands an energy form that can be applied with greater precision, efficiency, and cleanliness at the point of use, is compatible with the streamlined infrastructure of modern economies, and can be generated from a wide variety of sources. The result would be improved productivity with reduced energy intensity.

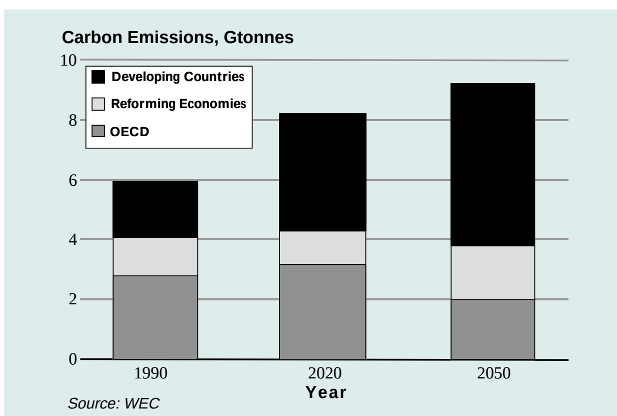
The broad availability of low-cost energy today masks the precarious nature of both the U.S. and world energy futures when considered against the demands for greater quantity and quality of energy in the coming decades, and the environmental risk that these demands pose. Without a major change in the structure and composition of the global energy system, the world will have limited means for dealing with the growing energy/carbon challenge. Although climate science remains uncertain, CO_2 and other greenhouse gas (GHG) emissions are considered by the Roadmap participants to be the key contingency upon which the global energy future hinges. The problem is compounded by the fact that by 2050, 85% of the world's population will be living in developing countries, and those countries will account for the major part of the world's GHG emissions.

The atmospheric carbon concentration guidelines of the UN Framework Convention on Climate Change (FCCC) require an aggressive shift to low- and zero-carbon energy technologies on a global basis in the 21st century—and application of methods for capturing and sequestering carbon during the transition. In the context of this energy/carbon challenge, electricity remains the most practical means of accelerating the historic trend of decarbonization of the global energy system.

However, today half the world's population exists on a few hundred kWh or less per person per year, while two billion more still lack any access to electricity. Achieving universal global electrification by 2050 will require bringing electricity to at least 100 million more people each year (up from the current rate of 40 million per year) and increasing average per capita consumption in today's developing world to at least that of the U.S. in 1950. Accomplishing this will require some 10 million MW of new electricity generating capacity worldwide by 2050.

This is an ambitious goal derived from the Roadmap deliberations and the participants' expectations that significant improvements in quality of life must be made available to the world's rapidly growing but least affluent population. (See Chapter 6 for a broader discussion of global sustainability issues.)

The burden of CO_2 emissions reduction will begin to shift to the developing countries.



The implications of this goal in terms of capital, construction, and technology are large. This means, for example, bringing on-line the equivalent of a 1000-MW power plant somewhere in the world every 2 days for at least the next 50 years while meeting ever-higher efficiency, environmental, and cost constraints. Moreover, by 2050 at least 50% of this new capacity will need to be carbon-free to meet the growing global environmental requirements of the new age. A first-order estimate of the capital requirements to achieve this Roadmap goal is \$100–150 billion per year on a global basis. This is consistent with the International Energy Agency (IEA) forecast of \$1.7 trillion to be invested in new power generation in the developing countries alone between 1995 and 2020.

While the 10 million MW of new electricity generating capacity needed over the next 50 years to support a sustainable future appears daunting, in fact, it represents less than the cumulative horsepower of five years of global automobile production. Also, the annualized capital cost of $100–$200 billion/year is less than the world now spends on tobacco, for example.

The Urgent Need for Environmental Knowledge

Environmental issues arose in almost all the Roadmap discussions—an indication of their central role in energy development and use in the coming century. Roadmap participants strongly supported improving the scientific understanding of environmental issues to guide both policy and technology strategies in the future. Also urgently needed are improved risk management tools for performing integrated assessments of the complex trade-offs among environmental and economic considerations. This recognizes that there is no environmental "free lunch" in terms of either energy service or the technologies for their use.

The value of gaining better scientific understanding of key environmental issues will escalate as policy proposals with increasingly greater economic consequences are put forward and debated. With so much at stake, the value of information that reduces the uncertainty of scientific issues already outweighs the cost of acquiring it, and this value will only grow with time.

The Roadmap places the highest priority on better understanding of the long-term risks associated with rising atmospheric GHG concentrations, as well as the potential pathways, and their cost to society, to achieve large reductions in GHG emissions.

Specific objectives for environmental research in the climate area include:

- Advances in global climate science, impact prediction, and integrated assessment capabilities to provide a strong and persuasive science-based rationale for mitigation and adaptation activities.
- A confident technology portfolio for addressing the climate issue. The UN Framework Convention on Climate Change (FCCC) calls for capping atmospheric greenhouse gas

Other Environmental Issues

Along with the climate change challenge, the world also faces a variety of urgent questions about the effects of human activity on the environment and how to control those activities to prevent environmental damage. Over the coming decades, understanding of many environmental issues will almost certainly progress substantially. However, it is unlikely that all environmental issues currently affecting the electricity industry will be resolved, and new issues will probably arise as the sphere of human activity increases. Thus, the Roadmap vision includes a continuing effort to develop better scientific understanding in key areas to help inform the debate on the future environmental and health issues affecting the production, delivery, and use of energy, as described below.

Tropospheric ozone: Emissions of NO_x and volatile organic compounds (VOCs)—the precursors of tropospheric ozone, or smog—are likely to remain problematic well into the next century. As recently as 1992, about 45 million people in the U.S. lived in areas where ozone concentrations exceeded current ambient air quality standards, and EPA is considering changes in the ozone standard that could require power plants to further reduce NO_x emissions. Heightened knowledge in the following areas could lead to better, more cost-effective responses to the ozone problem:

- The relative effectiveness of controlling NO_x emissions from power plants vis-a-vis controlling NO_x and VOC emissions from automobiles and other sources
- The role of precursor transport on ozone, especially to understand if NO_x or VOC emissions generated in one part of the country could form ozone that impacts a different region, and to create more realistic computer simulations of power plant emissions and transport
- The health and ecological effects of ozone, especially chronic human health effects of repeated ozone exposure

Trace emissions: U.S. industrial facilities that emit toxic materials in specified trace quantities are already required to employ specific pollution control technologies, and decisions on whether limits will be placed on toxic emissions from power plants are anticipated. To aid decision makers, risk assessment activities are examining the sources of air toxics, their atmospheric transport and transformation, human exposure patterns, and health consequences of exposures.

Current research efforts emphasize mercury, which is emitted from fossil-fired power plants, as well as from such sources as landfills, smelting, and gold production. Of particular concern—because of conflicting study conclusions—is whether mercury exposure is linked to neurological effects in school children.

Atmospheric particulates and precursors: Over the next 20 years, a concerted effort is needed to identify how human health is affected by airborne particulates generated by the combustion of fossil fuels. The complexity of this issue derives in part from the variety of sources that must be considered (power plants, vehicles, industrial sites, etc.), the large number of chemical species and chemical reactions involved, and the effects of particle size.

Although studies show a statistical association between particulate levels and human health, health effects must be further investigated via clinical, toxicological, and epidemiological investigations before the issue can be addressed in an informed and cost-effective manner. Observational data and analytical tools are needed to estimate the extent to which power plant emissions and other sources influence downwind particulate levels. Also required are models to simulate the transport of primary SO_x and NO_x to sulfate and nitrate aerosols, explain concentrations of other particulates of various sizes, and estimate resultant human exposures. Reducing these uncertainties will protect human health, most likely at a lower cost to society than policy decisions made without the benefit of this additional knowledge.

Water and land contamination: The complex interactions of a large set of processes contribute to the uncertainties surrounding the risks of water and land contamination. Knowledge of the biogeochemical cycling and toxicity of metals, metalloids, and organics discharged or leached and transported from power plants will provide insights on the "unit processes" that govern interactions between discharges and the environment. Research is also needed to determine the integrated effects of these discharges on aquatic and land ecosystems and on biodiversity.

Results of these studies should be incorporated into models for estimating the risks of contamination to humans and wildlife. These models must also integrate improved knowledge of the potential impacts of mitigation measures on electric power generation systems, including modifications to power plant cooling water systems, reductions in hydroelectric capacity, reduction of effluent streams, and cleanup of existing contaminated sites. The resulting models will help policy makers more accurately evaluate the benefits and costs of eliminating contamination.

Electric and magnetic fields: Research during the next 20 years can bring to closure, or at least significantly reduce, the uncertainty in the current debate about whether electric or magnetic fields cause cancer or other diseases. Achieving this goal will require improved methods for study design, integration of information, extrapolation from animals to humans, and risk assessment. These improvements will enhance the reliability of conclusions, lead to better understanding of potential impacts, and enable faster and more effective decision making.

Specific areas of uncertainty include explaining the association between wire codes (a measure characterizing the current-carrying capacity and proximity of distribution and transmission lines) and childhood leukemia suggested by some studies but not others; resolving conflicting findings regarding occupational exposure and cancer in the electric industry; determining a biologically relevant EMF "dose;" and addressing previously unanticipated links to other diseases, such as Alzheimer's disease and breast cancer.

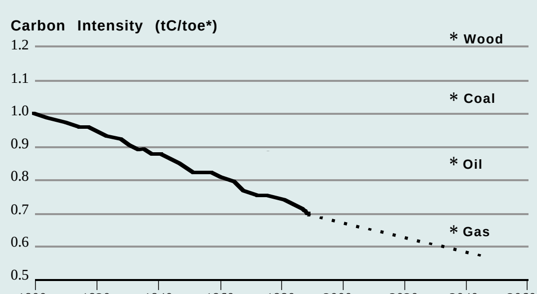
concentrations. This goal requires a transition to low-carbon energy supply and end-use technologies over the next century that can meet the FCCC's goal without severely constraining economic growth.

- Development and implementation of a realistic strategy employing "where and when" flexibility in global carbon reductions, as described in the next two sections.

Decarbonization of Energy

In order to cap atmospheric CO_2 concentrations at no more than 550 ppm (twice preindustrial levels), as recommended by the International Panel on Climate Change (IPCC), a global average emission rate of less than 0.2 kgC/kWh (kilogram of carbon per kilowatt-hour) will have to be achieved over the coming decades. With today's technology, the best achievable is about 0.9 kgC/kWh for coal, and 0.4 kgC/kWh for natural gas, according to the American Society of Mechanical Engineers (ASME). Even with continuous efficiency improvements, stabilization of atmospheric CO_2 concentrations will require a major commitment to zero-carbon alternatives for large-scale global deployment. Such alternatives do not exist today on the scale or at the cost required.

The carbon intensity of world primary energy must continue its historic descent if we are to reduce carbon concentration in the atmosphere.

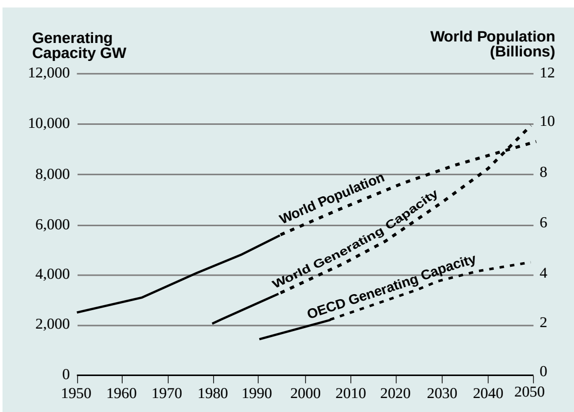


*Tonnes of carbon per tonne of oil equivalent
Source: National Academy of Engineering, 1997

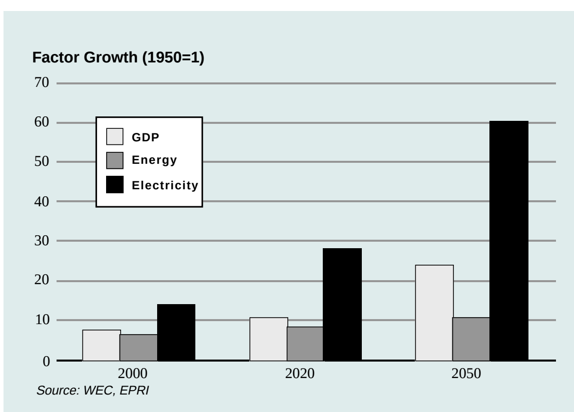
Considerable energy decarbonization progress has occurred over the last two centuries, facilitated to an ever-greater degree in this century by electricity. In the early part of the 19th century, wood yielded in time to coal, and in this century, to oil and natural gas—each with progressively less carbon per unit of energy. Decarbonization has made further inroads with the introduction of nuclear and commercial renewable energy. This progress, if maintained through technology advancement, puts the world on a predictable trajectory toward a clean, electricity- and hydrogen-based energy economy before the end of the 21st century. The range of progress among nations also shows how far most of the world economy is from best practices in decarbonization. The present carbon intensities of the Chinese and Indian economies, for example, resemble those of North America and Europe at the onset of industrialization in the 19th century.

As the world economy electrifies, coal and oil can drop from more than 60% of the global energy mix today to the margin by 2100. In the past, decarbonization has occurred as a natural outcome of the economic drive for cost reduction and efficiency improvement. In the future, the economic drivers will be supplemented by environmental concerns related to GHG emissions and other pollutants from fossil generation.

Global electricity generating capacity will climb to meet the needs of a growing population.



Globally, electricity growth helps to "pull" economic growth due to higher efficiency, while diminishing primary energy growth.



Energy Scenarios and Goals

Scenario analyses performed by a variety of domestic and international organizations yield a wide range of energy consumption projections—but nearly all scenarios reflect substantial electricity capacity growth requirements to satisfy the current surge in global population. The World Energy Council and the International Institute for Applied Systems Analysis (WEC/IIASA) have defined a series of such scenarios, ranging from high growth to "ecologically driven." (See Appendix B.)

The WEC scenarios were used to help frame the initial discussion among the Roadmap participants and then became a point of departure for more in-depth investigations of electricity's role in global

Table 5-1 Global Economic and Energy Goals			
	1950	**2000**	**2050**
Population (billion)	2.5	6.2	10
Gross world product (trillion 1990 $US)	4	32	100
Primary energy (Gtoe)	1.5	10	17
Electricity fraction of primary energy (%)	20	38	70
Electricity conversion efficiency (%, global average)	28	32	50
Electricity generating capacity (thousands of gigawatts)	0.2	3	10
Capacity factor (%, global average)	50	50	70 (1)
Electricity consumption (trillion kWh)	1	13	60 (2)

(1) Capacity factor for central station power
(2) Includes 10 x 10^{12} kWh for electricity-based transportation
Sources: UNDP, WEC, DOE/EIA, EPRI analysis

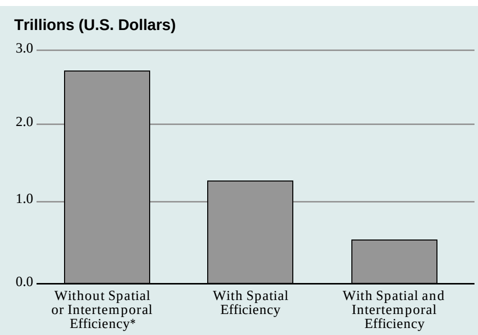
development. After exploring the technological potential of electricity-based innovation, the participants identified a set of goals that appeared to maximize the economic and environmental value of accelerated global electrification (see Table 5-1). In effect, these goals combine the economic development benefits of the various WEC high-growth scenarios with the resource conservation benefits of their ecologically driven scenarios (see Appendix B). Under these conditions, the electricity fraction of total primary energy consumption reaches 70% by the year 2050, while the efficiency of the entire energy chain doubles. Stated in terms of WEC scenarios, the Roadmap scenario targets electricity consumption at about 50% greater than that in the WEC growth cases, but with a primary energy structure that more closely reflects the WEC's ecologically driven cases. This universal electrification goal will provide an annual average per capita electricity consumption of 3000 kWh in the developing world, with approximately 1000 kWh going to its poorest inhabitants. It will reduce the demand on scarce resources and promote economic development and education in the least affluent regions of the world, thus helping to slow global population growth.

As noted above, this goal implies increasing the rate of electrification from 40 million new users per year to at least 100 million per year, and bringing new generating capacity online at the rate of ~1000 MW every 2 days for the next 50 years. Under these scenarios, electricity consumption is expected to reach approximately 60 trillion kWh/year by 2050 (roughly four times today's consumption) including 10 trillion kWh/yr for transportation. Meeting this global electrification goal in a sustainable manner requires an urgent R&D program now to develop economically accessible low- and zero-carbon generation technologies within 20 years.

"Where and When" Flexibility in Emissions Reduction

Within the context discussed above, the Roadmap assessment of climate change focuses on the need to coordinate the timing of CO_2 emission controls with the availability of advanced technologies that can substantially decarbonize the production of electricity. To see why this is important, consider how power producers are likely to respond to near-term reductions in CO_2 emissions as exemplified by the 1998 Kyoto accords. Given current generation technologies, producers are expected to meet the growth in electricity demand chiefly by using natural gas combined-cycle plants to replace a significant fraction of existing coal capacity. Assuming the necessary availability of natural gas, calculations suggest that this strategy could be made to work until about 2030, but at the sacrifice of fuel diversity and with the probability of a significant increase (30–50%) in the price of both electricity and natural gas.

"Where and when" flexibility can greatly reduce the cost of achieving a 20% cut in OECD emissions.



*Requires 20% cut in OECD emissions from 1990 levels by 2010, with no trade in emission rights with other regions

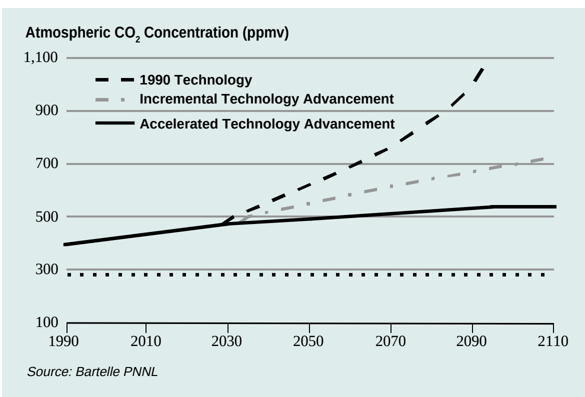
Source: Richels et al.

Under this scenario, natural gas would have to fuel more than 75% of U.S. electricity generation by 2030, with coal relegated to less than 15% of generation. However, after 2030, it would no longer be feasible to meet demand growth and sustain CO_2 emission reductions merely by building new gas-fired plants. Based on historical precedent, Roadmap participants expressed concern that such short-term, rigid command and control restrictions on carbon could discourage needed progress in generation technology development for an extended period, at high cost to the economy and ultimately to the environment as well. Such restrictions also reflect an implicit assumption that the unpredictable geopolitics of energy supply can be controlled over an extended period to U.S. advantage without the need for domestic energy diversity.

Fortunately, the long-term global nature of climate change allows flexibility to develop a more rational and sustainable alternative. Most greenhouse gases have a long atmospheric life, and it is their cumulative emissions over a long period of time, not the emissions from a single region or in a single year, that determine atmospheric concentrations. Many possible profiles of carbon emissions versus time can produce the same atmospheric concentration. What really matters is not exceeding the allowable cumulative carbon emissions limit that corresponds to a specific atmospheric CO_2 concentration target. For example, to stay within a concentration of 550 ppm, the cumulative global carbon emissions limit is approximately 1000 gigatonnes of carbon (GtC) over the coming century. With the technology advancements envisioned here, the world can achieve a practical, carbon-free energy economy before the end of the 21st century.

This requires a global strategy that takes advantage of the long atmospheric time constant of carbon to enable flexibility in the locations and timeframes of needed CO_2 reductions. While providing much greater assurance of safely limiting atmospheric CO_2 concentrations, "where and when" flexibility can also dramatically reduce the cost involved. The effectiveness of reducing emissions wherever it is most economic is well accepted scientifically and can reduce the cost of achieving a specified concentration by over 50%. Moreover, allowing flexibility in the timing of reductions can

Stabilization of atmospheric CO_2 concentrations will require accelerated technology advancement.



reduce the cost still further by incorporating more efficient generation systems and lower-cost carbon capture and sequestration technologies as they become available.

The performance goal in the strategy should be to improve the global rate of reduction in energy intensity (E/$GDP) from 1%/year to 1.5%/year, and the rate of energy decarbonization from 0.3%/year to 1%/year by 2050 in order to stay within the 1000 GtC emission budget.

Cost reduction is an essential ingredient in resolving the policy dichotomy between industrialized and developing countries over carbon reduction. Currently, the economic penalties of reducing carbon emissions place an intolerable burden, particularly for the developing world. In contrast, "where and when" flexibility reduces the cost for all parties, and can form the basis for a carbon permit trading system that has the potential to further reduce costs for developing countries, while facilitating their economic development.

The Need for a Robust Portfolio of Generation Options

The carbon-free options can make up a progressively larger share of the generation portfolio—continuing the long-term trend of declining carbon concentration in the global fuel mix.

Changing from a global system where more than 85% of the energy used releases carbon, to a system where very little carbon is released, requires fundamental changes in technology and major investments in capital equipment turnover or replacement. Anticipated incremental advances in today's technologies will be inadequate to meet the global energy performance specifications of the future. A robust portfolio of advanced power generation options—fossil, renewable, and nuclear—will be essential to meet these growth requirements, both domestically and globally.

The portfolio strategy offers the greatest flexibility and resiliency in meeting the uncertainties of the future, as well as the opportunity to seize technical breakthroughs wherever and whenever they occur. As described in Appendix B, a number of factors can shift the balance of the portfolio, including the availability and price of fuels, the pace of technological advancement, capital requirements, regulation, and policy. One critical example is the trend of internalizing the environmental costs of energy, which will increase the relative importance of renewable and nuclear energy development.

Coal will continue to be the backbone of global electricity generation well into the 21st century. It is a vast resource in key markets as diverse as the U.S., China, and India, all with strong economic and security incentives to use their indigenous resources. Shifting from this dependence on coal and other fossil fuels to a carbon-lean global economy will require several key actions over a long transition period:

- R&D investments in innovations to enhance the efficiency and environmental performance of fossil generation technologies, including, for example, combustion turbines, and integrated coal-gasification combined cycles.
- Development of lower-cost carbon sequestration technologies to increase the environmental acceptability of fossil fuel.
- Cost reductions for a diverse array of distributed power supplies, which could satisfy a significant portion (15–25%) of the global demand for new capacity. This includes fundamental breakthroughs to decrease the cost of renewable energy to allow large-scale global deployment of off-grid systems, particularly in the lower-energy-density and rural economies of the developing countries that will still be home to at least a quarter of the world's population in 2050.
- Breakthroughs in nuclear generation to reduce the obstacles to greater use of what is likely to be the only non-carbon option that can be deployed on a sufficiently large scale to meet 21st century global power requirements.

Over at least the next 20 years, the developed world will largely meet the need for additional capacity with gas-fired combustion turbines.

Fossil Generation Technology Priorities

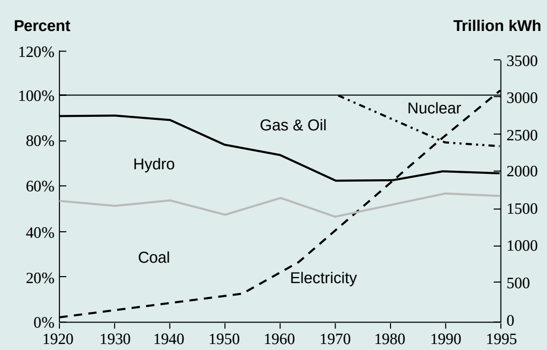
As part of this realistic transition, fossil fuels will continue to dominate the global energy scene through at least the middle of the new century. R&D investments should be directed to enable this vital transitional role in the most efficient manner. Emphasis is expected to be on building an efficient "methane-based" energy economy, which represents the next stage of decarbonization.

Natural-Gas-Based Technologies Over at least the next 20 years, the developed world will largely meet the need for additional capacity with gas-fired combustion turbines.

Continuing to push the efficiency of combustion turbine technology is a high R&D priority because the turbines themselves will be key components in every future high-efficiency combustion system, as well as in advanced gas-cooled nuclear plants, for example. Conversion efficiencies are expected to exceed 60% of the lower heating value (LHV) of the fuel, based on advances in turbine design and materials technology. In the 2020–2050 timeframe, combined cycles using gas turbines with fuel cells could push the efficiency to 80%. Fortunately, there is considerable market pull for these needed developments.

An interesting strategic concept is the fossil-fueled zero-emission power plant (ZEPP) described by Ausubel *et al*. They envision a high-efficiency turbine system fueled by methane in a supercritical CO_2 carrier, and producing liquid CO_2 as a by-product. Aker Maritime in Norway has recently announced an initiative to develop a similar ZEPP alternative. Developing a ZEPP for commercial applications will require breakthroughs in turbine design, high-pressure systems, materials for high temperatures and pressures, and long-term CO_2 storage. While unqualified success is speculative, each of these breakthroughs would make valuable synergistic contributions in its own right to other energy technology needs.

Coal has supplied one-half of the fuel to meet domestic electrification growth throughout the 20th century.



Source: WEC, EIA

Clean Coal Technologies For coal-based generation, the principal driver is the need to increase efficiency and reduce emissions while decreasing capital and operating costs. Clean-coal technologies, such as integrated gasification combined cycles (IGCC) operating on synthesis gas, and pressurized fluidized-bed combustion (PFBC), have the potential to achieve 50% efficiency in terms of higher heating value (HHV) at the same cost of electricity as equivalent natural gas combined-cycle systems. This depends on lower fuel cost to help offset the higher capital cost of coal-based options. Current estimates suggest that these technology advances have the potential to make new clean-coal generation competitive with gas on a cost-of-electricity basis in the 2010 to 2020 timeframe.

As another example, DOE's Vision 21 includes a coal refinery or "powerplex" concept with hydrogen separation, chemical production, and carbon dioxide sequestration in addition to electricity generation. The result would be far more efficient and complete utilization of coal's total resource value. But this technology will require major infusions of R&D funding to achieve commercial viability before 2020.

Carbon Sequestration Economical carbon capture and safe, long-term storage technology will be needed to extend the environmental lifetime of fossil fuels within a global carbon emissions budget. Sequestration reduces the "net CO_2 venting" of fossil fuel use, either by capturing the CO_2 at the point of generation and storing it over the long term in sinks, or by transferring CO_2 from the atmosphere. Potential sinks include geological formations and terrestrial ecosystems, as well as the ocean. The worldwide terrestrial carbon reservoir is larger than the atmosphere, and the ocean reservoir is larger still. Many environmental, chemical, and physical challenges remain to be resolved, however, as part of the larger R&D agenda in this area.

Costly, low-efficiency carbon capture technology is in commercial use now, principally for the production of high-purity food-grade CO_2 and for enhanced oil recovery. Research is needed to develop lower-cost technologies that operate at ambient temperature and pressure, and to demonstrate long-term storage technologies. Studies are also needed to evaluate opportunities for removing CO_2 from the atmosphere biologically through no-till and low-till agriculture, afforestation, and the "fertilization" of the ocean. DOE is completing a research roadmap to advance the science and technology of sequestration in response to these needs. The International Energy Agency greenhouse gas R&D program is sponsoring technology investigations as well.

Sequestration is valuable for both the carbon reduction it achieves and its role in moderating the risk of investing in future fossil-fuel-based generation. That risk hinges on the

In the future, carbon capture and long-term storage technology may be needed to preserve the fossil option.

uncertainty regarding future limitations on greenhouse gas emissions. However, the availability of low-cost sequestration has the potential for removing or at least loosening the connections between fossil fuel usage and carbon emissions, and thus gives the potential investor greater confidence in deploying and operating fossil (and in particular, coal) plants.

A related issue is the amount of sequestration that will be needed. As discussed above, a "carbon emissions budget" limited to approximately 1000 GtC over the next century is an insurance measure to confidently maintain a safe atmospheric CO_2 concentration within the IPCC cap of 550 ppm. Sequestration systems do not have to remove all the carbon from power plant flue gas streams, as long as cumulative emissions remain within the budget. In this context, it's important to treat carbon removal and sequestration as solution alternatives addressed through consideration of cost-effectiveness, rather than to pursue extremely high removal rates at all costs.

Nuclear Power Revival

Nuclear power was acknowledged to have the most potential to contribute reliable carbon-free power generation on a large scale.

Not surprisingly, the discussion of nuclear power was one of the most spirited of the Roadmap workshops. Nonetheless, nuclear power was acknowledged to have the most potential to contribute reliable carbon-free power generation on a large scale over at least the next half century. The Roadmap participants also noted that nuclear power remains an exceptionally "brittle" technology today. A significant plant safety or discharge event anywhere in the world could instantly negate in the public's mind an established, long-term track record of superior nuclear plant operations. It is therefore essential to the future of nuclear power that all operators worldwide maintain and strengthen their active collaboration on best practices and technology.

For nuclear to be a major element of the future generation portfolio, technology advances are needed to increase both fuel utilization (only a few percent of the energy contained in nuclear fuel is used in current plants) and the thermal efficiency of electricity generation, while reducing costs to make nuclear power competitive with other options. U.S. leadership in nuclear power technology was also cited as essential to maintaining credible influence on other nations' nonproliferation policies, and on nuclear safety worldwide through encouraging the most effective technology and infrastructure.

Significant obstacles that must be overcome in achieving these advances include:

- Public concerns about the safety of new nuclear generation and the potential for nuclear weapons proliferation.
- Lack of credible capabilities for long-term storage or reuse of spent fuel.

Well-defined technology development opportunities that address these limitations include:

- High-utilization fuel cycles to improve generation economics, extend nuclear fuel resources by up to a factor of 80, significantly reduce residual waste toxicity, and alleviate proliferation concerns.
- High-temperature gas-cooled reactors for higher efficiency and process heat applications in addition to electricity generation. Pebble-bed reactor designs such as proposed by ESKOM in South Africa could, for example, allow modular construction down to the 100-MW size range.
- Transmutation of nuclear waste into non-radioactive or short-lived isotopes.
- Secure facilities for spent fuel management and long-term waste disposal.
- Continued development of fusion power, which could lead to a breakthrough in energy alternatives in coming decades.
- Implementation of a risk management approach to regulating nuclear plant design and operation.

In each case, it is the commitment, not the technological means, which is missing. The creation, exemplary safety record, and public acceptance of the U.S. nuclear navy was cited as a benchmark example of the success that uncompromised technology and unwavering commitment can achieve. In the next decade, a proactive dialog between the industry and the public on the issues of nuclear power in the context of a sustainable energy future is seen as essential to rebuilding the needed commitment.

Scaling Up Renewables

The hope for significant displacement of fossil fuel will increasingly rest with the new forms of renewable technology.

Both traditional and "new" renewable energy sources will be important contributors to the global energy system. However, the hope for significant displacement of fossil fuel will increasingly rest with the new forms of renewable technology.

The traditional renewable energy resources, hydro and biomass, are expected to maintain their current percentage contribution (8%) to world energy supply through at least the year 2020. Currently, 660 GW of hydro capacity alone is in place worldwide. In addition, two-thirds of the world's economically feasible hydropower potential is held by the developing countries and will undoubtedly be aggressively developed. Biomass, on the other hand, faces a less certain future. Traditional, noncommercial biomass use is likely to shrink as cost-effective and more efficient commercial energy opportunities increase in the developing world. In its place, commercial biomass energy systems based on gasification may make inroads, especially in rural settings, as a way of using agricultural wastes. However, Roadmap participants pointed out that large-scale use of biomass for electricity generation carries offsetting penalties in terms of the low efficiency of photosynthesis, the resulting vast land requirements, and the potential for ecosystem damage. These considerations are likely to limit the introduction of commercial biomass systems in sensitive regions.

On the other hand, "new" renewables are expected to contribute increasingly to global development. The challenge is to find practical ways to harness these readily available but diffuse and intermittent energy sources. The dominant options foreseen by the Roadmap participants are wind, solar photovoltaics (PV), and geothermal in certain locations. Thin-film PV costs are estimated to fall from $6/W today to $1.10/W in 2020, and $0.90/W in 2030, based upon the evolution of current technology. But given the rapid pace of development in the material sciences, new technologies with even greater performance improvements are likely over the next 20 years, resulting in increased conversion efficiency, lower cost, and wider application.

Without such breakthroughs, these new renewable options are expected to be limited to providing 2% or less of the world's electricity over the next 30 years. Growth beyond this percentage will require not only breakthroughs in energy conversion, but a long-term, reliable, and maintenance-free energy-storage capability that can be integrated with renewable power sources. For example, developments in electrolytic hydrogen, batteries, flywheels, and other storage technologies may have the potential to extend the use of intermittent renewables. Nonetheless, each of these new renewable systems carries its own set of environmental impacts. Such impacts must be resolved if the systems are to achieve their full potential.

Even at a relatively low fraction of total world energy consumption, dispersed renewable generation can play a primary role in rural settings by providing energy and economic opportunities that are now missing. Deployment of dependable small-scale renewable generation technology in rural areas will cost much less than dealing with the effects of poverty in the mega-cities of the 21st century.

Fortunately a large portion of the developing world is in the "solar belt," where the high rate of insolation presents significant solar renewable opportunities. One example is an integrated solar/natural gas combined-cycle pilot project now underway in Egypt. Similar projects could be conducted on a large scale in the desert extending along the southern Mediterranean coast. ESKOM and Shell International Renewables, Ltd., have also announced a plan for a solar power development venture in rural South Africa inaccessible to the national electric power grid. This venture will provide stand-alone solar power units to as many as 50,000 homes currently without electricity at a cost of about $8 per month. The power units are capable of powering three low-wattage lamps and a small TV or radio for 4 hours/day at an expected cost of about $800 to manufacture and install.

The real promise of renewables may not lie in the technologies in the current R&D portfolio.

However, the real promise of renewables may not lie in the technologies in the current R&D portfolio. Technologies that are on the horizon could revolutionize the generation of electricity in a low-carbon future. Some new approaches include:

- **Solar power satellites**—satellite-based systems that collect the entire electromagnetic spectrum emitted by the sun, convert the energy to microwaves, and beam it to terrestrial receivers. First studied over 20 years ago and discarded as being prohibitively expensive, this technology deserves another look in light of the rapidly advancing technologies for launch vehicles, satellites, and energy transmission.

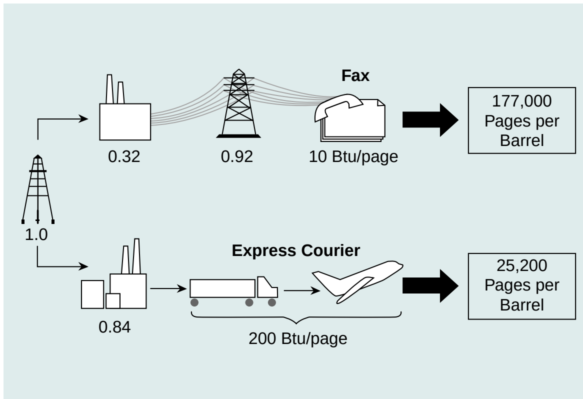
- **Biomimetic technology**—artificial systems that mimic the chemical and physical processes of living systems, including enhanced light-gathering capability or artificial photosynthesis to enhance the efficiency of renewable generation.
- **Hydrogen as an energy carrier**—biological, electrochemical (e.g., using nuclear electricity), or thermal production of hydrogen gas, which in turn is used to transport and store energy. Fortunately, hydrogen can be manufactured from water, can substitute for most fuels, and its combustion back to water vapor does not pollute. Changing to hydrogen as a carbon-free energy carrier would also enable distributed uses of energy (both stationary and mobile) to avoid greenhouse gas emissions at the point of use. This possibility of creating a hydrogen economy is already being investigated as a commercial venture in Iceland. The primary energy used there today comes from hydro power and geothermal heat plus oil. There is considerable potential for further exploitation of the renewable sources of energy to produce hydrogen and offset oil. The Iceland Hydrogen and Fuel Cell Company, Ltd., venture will test various uses of hydrogen, or hydrogen carriers with fuel cells, with the objective of converting both public and private transportation.

In summary, technology advances can enable carbon-free dimensions to confidently make up a progressively larger share of the generation portfolio—continuing the long-term trend of declining carbon concentration in the global fuel mix.

Improving End-Use Efficiency

As discussed in Chapter 4, improving the efficiency of electricity end uses has been an important factor in stimulating economic growth and productivity improvement. In developed countries, the energy intensity of economic growth has decreased steadily as electrification has progressed. Continuation of this trend and its extension to the developing world will not only stimulate global economic growth, but also reduce primary energy requirements and thus help decarbonize the energy sector.

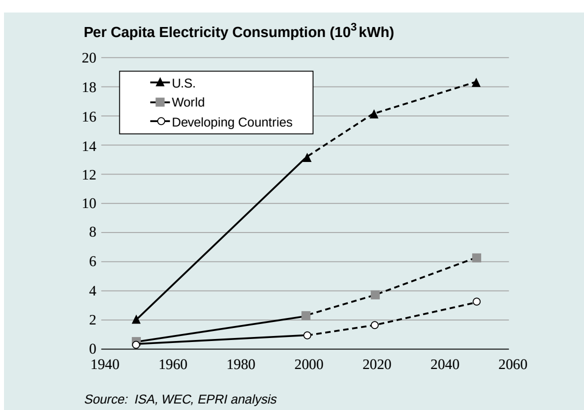
Fax machines are 7 times as energy efficient as express couriers. Internet communications increases the energy efficiency gain by at least another order of magnitude.



Electrotechnologies can accelerate efficiency improvements and decarbonization in several ways. Some technology advances will improve the efficiency of existing applications, such as high-efficiency lighting and motors. Other electrotechnologies will replace existing fossil-fueled equipment but operate at higher efficiency, as in the substitution of all-electric and hybrid electric vehicles for gasoline-powered cars, or the use of high-efficiency heat pumps for home and commercial building applications.

Finally, some electrotechnologies will introduce completely new processes to improve both energy efficiency and productivity simultaneously. An example is microwave synthesis of ethylene, which replaces a chemically driven cracking process with a microwave process that consumes far less energy by breaking and forming only the chemical bonds required to complete the reaction. Moreover, it creates a much smaller and less hazardous waste stream. Another example is the use of information technology to perform completely new functions, e.g., enabling customer-managed service networks (Chapter 3), rather than just automating existing tasks.

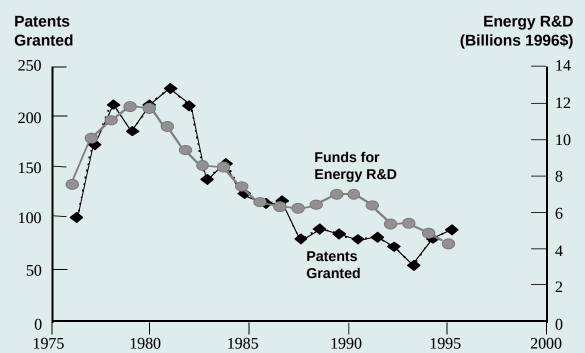
In 2050, per capita electricity consumption in the developing countries will exceed the 1950 U.S. level.



Projections of future electrification suggest that it will be possible to reduce the energy intensity of economic growth by approximately 50% over the next 50 years, with about half this improvement resulting from end-use efficiency improvements. Thus, end-use efficiency gains have the potential to reduce both energy and carbon emissions per unit

GDP by >25% by 2050. As a result, the 3000 kWh projected as the average per capita electricity use goal in developing countries by 2050 will go much further in terms of providing lighting, space conditioning, industrial energy, computing, communication, etc., than an equivalent amount of electric energy used in the U.S. in 1950. Already, for example, the manufacturing and widespread use of compact fluorescent bulbs, for reasons of both energy efficiency and export potential, has become a priority in China.

Energy technology innovation is very closely tied to R&D levels.



Source: Margolis and Kammen

Energy R&D Requirements

Given the magnitude of energy requirements for the future, there is an urgent need to increase electricity generation and end-use R&D by at least $2 billion/year, shared between the public and private sectors. Further, given the demographic and environmental challenges of the next 50 years, these resources should be focused on knowledge development in the essential environmental sciences, technical breakthroughs in non-carbon energy sources, and wiser, more intelligent use of energy through more precise digital control and miniaturization of processes.

This increase in energy R&D investment is consistent with the 1997 conclusions of the Energy Research and Development Panel of the President's Committee of Advisors on Science and Technology (PCAST), but goes beyond the PCAST report in the scope and pace of the recommended research program:

> *PCAST endorses the findings that this country's economic prosperity, environmental quality, national security, and world leadership in science and technology all require improving our energy technologies, and that an enhanced national R&D effort is needed to provide these improvements. The inadequacy of current energy R&D is especially acute in relation to the challenge of responding responsibly and cost-effectively to the risk of global climate change.*

> *The report recommends an increase, over a five-year period, of $1 billion in the DOE's annual budget for applied energy-technology R&D. The largest shares would go to R&D in energy efficiency and renewable energy technologies, but nuclear fusion and fission would also receive increases. R&D on advanced fossil-fuel technologies would change in favor of longer-term opportunities, including fuel cells and carbon-sequestration technologies.*

There is also a significant role for the federal government in encouraging teaming, partnership, and collaboration with the private sector, the states, and other nations during this rare window of opportunity to rebuild the global energy system for 2020 and beyond. As part of this joint effort, additional support is needed for basic research at the universities and National Labs, along with enhanced bottom-up private sector leadership for short-term commercial development. This will require new and stronger incentives for collaboration among all potential organizations contributing to technological advancement directed toward enhancing economic productivity and addressing the demographic and environmental challenges facing the world.

The key technology targets and corresponding knowledge gaps in the generation area are summarized in Table 5-2, along with first-order estimates of annual R&D funding requirements for at least the next 10 years.

Solving this energy/carbon conflict is considered by the Roadmap participants to represent a critical milestone toward achieving a more holistic approach to environmental progress. The issue is precedent-setting both in its global nature and scale, and in the strategic challenge it poses. Its resolution demands reconciling economic aspirations with environmental protection in the context of a world population that is expanding at an unprecedented rate, but for most, only at a subsistence level of development. In short, the energy/carbon conflict must be addressed as an effect stemming from the underlying "trilemma" of population, poverty, and pollution. Meeting the challenge created by this trilemma is the ultimate Electricity Technology Roadmap destination, as discussed in Chapter 6.

Table 5-2 Energy/Carbon Conflict R&D Funding Requirements				
Targets	**Critical Knowledge Gaps**	**10-Year Funding Outlook ($ million/year)**		
		Current Funding	**Incremental Future Funding Needs**	**Total Funding Needed**
Increase natural gas central station efficiency to >70%	• Materials to withstand high temperature and pressure in high-efficiency designs • Innovative cycle designs	100	100	200
Reduce emissions of gas-fired distributed generation systems by half	• Ceramic blades and recuperators for gas turbines to increase operating temperature and improve efficiency • Materials for high-reliability fuel cells	<100	100	200
Improve the thermal and resource efficiency of coal-based generation to reduce emissions by half	• High-temperature materials for ultra-supercritical steam cycles • Hot gas cleanup for gasification and PFBC systems	100	200	300
Commercially viable advanced co-production systems (coal and biomass refineries)	• Higher efficiency and reduced emissions associated with coal processing through low-cost air separation and advanced catalysts, and coal and biomass process development	<100	200	300
Carbon capture and sequestration technology with cost <$40/tonne of carbon	• Assessments of feasibility and environmental acceptability of final storage methods • Low-cost ambient temperature and pressure capture methods	100	300	400
Cost-competitive renewable generation technologies	• Reduced footprint and cost of solar and wind generators through increased efficiency; low-cost mass production • Reliable maintenance-free distributed renewable power system for rural and remote locations	300	400	700
Public acceptance of a new generation of cost-competitive nuclear power plants	• Resolution of safety and proliferation concerns • High-fuel-utilization designs • Short construction times and low initial cost • Coproduction of hydrogen for use as energy carrier	<100	500	600
Environmental knowledge base for global climate change	• Confident global models and assessments of the science and impacts of global climate change • Strategies and policies that protect the environment at least cost for all global users	700	200	900
Total Funding		**1,600**	**2,000**	**3,600**

6 The Global Demographic Challenge

...Managing the 21st Century Population Boom

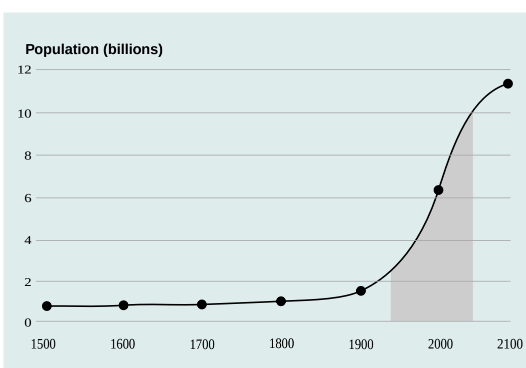
A century ago the historian Henry James observed that "the law of human acceleration cannot be supposed to relax its energy to suit the convenience of man." That law of human acceleration is hurtling us now into a new century and a new age. The world James lived in contained fewer than two billion people. Today, we add nearly a billion every decade. The Industrial Revolution extended over generations and allowed time for human and institutional adjustment. Today's information revolution is far swifter, more concentrated, and more drastic in its impact.

In fact, the global demographic challenge in this accelerated world context can be viewed as either the ultimate roadblock or the ultimate opportunity. The world is in the midst of a population explosion that represents one of the greatest challenges of the next century as well as the greatest economic opportunity in history, and quite possibly, the world's greatest blind spot. This blind spot has several dimensions. First, because of the difficulties in seeing the problem holistically, there is a tendency to take narrower points of view out of context: food, family planning, structural reform, law, climate, business, energy, economic development, biodiversity, etc. Second, the competitive world demands quick financial return, wherein the economic incentives severely discount the future value of almost everything. And third, there is a general lack of patience—a tendency to grab for quick, single-answer solutions to complex problems that unfold over many decades.

The sustainability issue was first raised on the world stage in 1987 by the United Nations Commission on Environment and Development, the so-called “Bruntland Commission.” The Commission defined sustainable development as growth that meets the needs of the present generation without compromising the ability of future generations to meet their needs. Sustainability is about unlocking economic and social development opportunities for all of mankind without creating irreversible damage to the biosphere or irreversible loss of the earth’s diverse natural resources. Roadmap participants underscored this essential goal as in everyone’s enlightened self-interest. But meeting this goal in a heterogeneous world of 10 billion people will require an unprecedented commitment to technological advancement with immediate global access to the results.

This commitment is seen by the Roadmap participants as a necessary precursor to sustainability, but it alone does not assure a sustainable world. All the opportunities created by science and technology can be negated by the misery of wars and destructive social conflicts. The commitment, therefore, must be to more than simply unlocking opportunities; it must be to the ever-wiser use of these opportunities as well. Economic growth needs to be concerned with more than merely generating income: It is also about expending it in ways that can positively influence human lives by expanding the choices available to ordinary people.

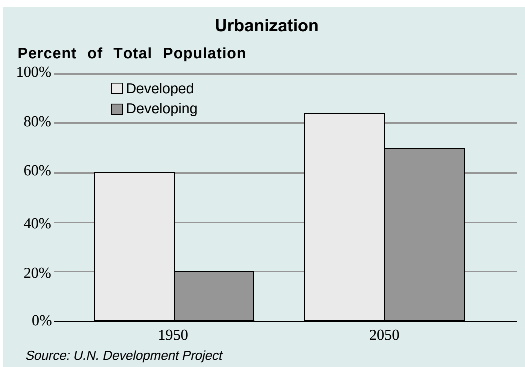
We’re now in the midst of the greatest population explosion in history.



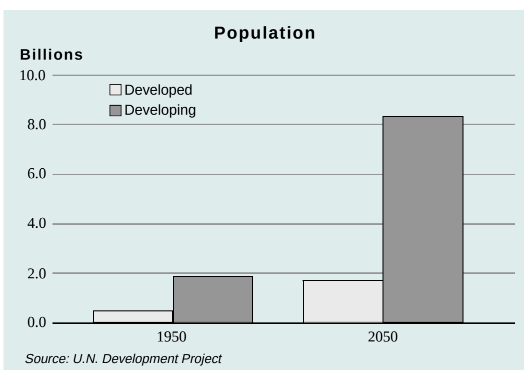
The Driver—Population and Urbanization Trends

The most significant driver of change is the unprecedented expansion in global population. Population has doubled since 1950 and may nearly double again by 2050 to 10 billion people, with some 90% of the growth occurring in today’s developing nations. If replacement fertility were uniformly achieved throughout the world today, population would stabilize at about 9 billion by 2050. The more plausible scenario is that fertility levels will continue to vary significantly, with many regions still far above the replacement level, most notably in Africa and Southern Asia. This will likely lead to continued global population growth beyond mid-century. The impoverished condition of most of the world's inhabitants adds to the difficulty of providing minimal levels of education and economic opportunity. Just in the past 15 years, per capita income has declined in more than 100 countries, and 1.3 billion people still live on less than $1 a day. Further, 1 billion people have no access to a safe water supply, and 2 billion lack sanitation. Over 2 billion have no access to commercial energy of any form. Rather, they depend on locally available, nonrenewable biomass for cooking and heating, thereby depleting the very resources they need to survive.

Urbanization is growing even faster than population.



90% of world population growth is occurring in developing countries.



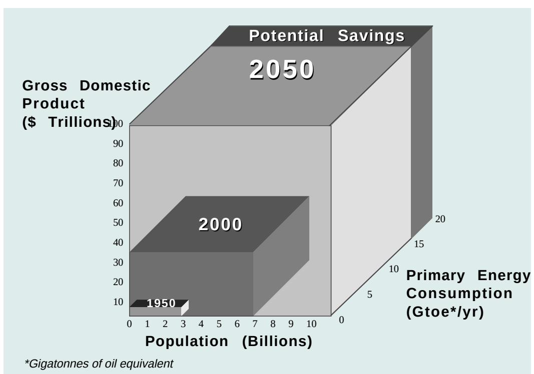
Urbanization is also growing, as impoverished people seek opportunity by migrating to cities. Unfortunately, that opportunity is lacking for most in the developing world. Nevertheless, by 2050 there will likely be more than 60 mega-cities with populations over 10 million each—compared to 15 such cities today—again predominately in the developing world. Most of these rapidly growing mega-cities lack the essential infrastructure capabilities to support the influx of new arrivals. Housing, sanitation, health services, transportation, and energy needs outweigh available services as the burgeoning cities attempt to keep pace.

Beyond certain limits, demographic expansion creates diseconomies of scale, reversing a trend that seems to have dominated much of human history, when open and available territory in the world served as a demographic outlet. For example, until recently urbanization and improved economic conditions were generally seen as synonymous. Today, however, the extraordinarily rapid growth of urbanization, particularly in the developing world, creates social, sanitary, and environmental problems which outstrip the economic ability to support that growth. The result threatens to reverse the historic connection between cities and civilization.

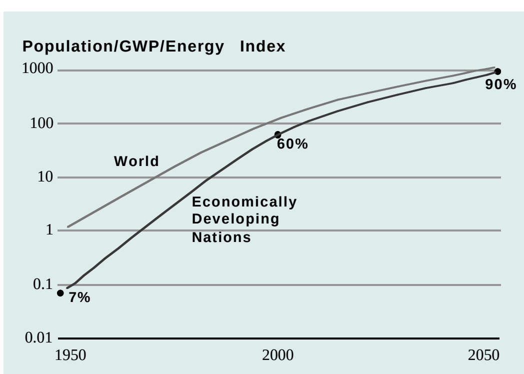
Global Footprint

The number of people is only one dimension of mankind's "footprint" on the planet. Multiplying population by gross world product and by global primary energy consumption provides some perspective on the scale of mankind's impact. The resulting "volume" of that global footprint in 2050 will be about 1000 times that of 1950. Today it is about 100 times the 1950 volume.

Mankind's footprint will be 1000 times larger in 2050 than in 1950.



By 2050, the developing nations will account for 90% of the global footprint.



Note that the dimensions of the footprint are interdependent. Moderating population, for example, requires economic development, which in turn requires resources and energy. In fact, the only practically available action to reduce the size of the footprint in the short term is to improve the efficiency of resource and energy utilization. In particular, electricity and the greater efficiency it provides have the potential to progressively reduce the volume of the global footprint at least 25% by 2050.

The sustainability burden is also shifting rapidly toward today's poorer nations. In 1950, the economically developing countries represented less than 10% of the volume of the global footprint. Today they represent about 60%, and by 2050 they will account for nearly 90% under "business as usual" conditions. The shifting imbalance is a point of contention in policy debates, and will be a source of continuing friction. This is all the more reason to create technological solutions that can help ameliorate the political tensions.

The goals of the Roadmap are to reduce the demand on resources without sacrificing the global economic growth essential to sustainability.

Technology Foundation for Sustainability

To put the world on a path to economic and environmental sustainability by mid-century, the advanced technology foundation needed for large-scale deployment of new energy and other infrastructure systems must be in hand within 25 years. Accelerated development of these technologies is therefore urgent. Minimum requirements include:

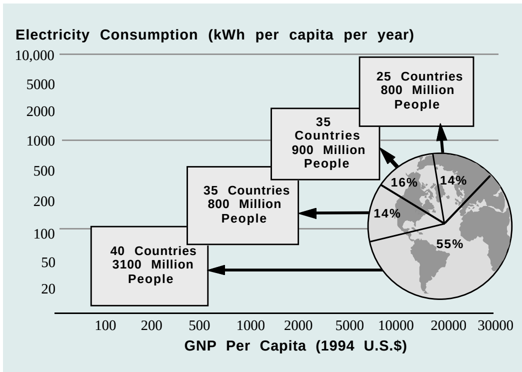
- A robust, clean, and affordable electricity supply technology portfolio, with sufficient breadth to be applicable to all stages of economic development (see Chapter 5)
- The extension of a mega-infrastructure of electricity and communications (described in Chapters 2 and 3) to developing countries to serve as an essential platform for economic progress
- Enhanced support for R&D, education, and infrastructure sufficient to sustain the pace of innovation in critical fields of science and technology (described in Chapter 4)
- Accelerated global diffusion of technology and best practices in agriculture, energy, and fresh water supply
- Affordable, efficient, and competitive electric transportation technology
- The practical capability for urban and industrial ecology to streamline the infrastructure of cities and industries to achieve greater efficiency and near-zero waste

This global program will require multibillions of dollars per year in public and private investment for research, development, and deployment in advanced transportation, industrial, agricultural, and urban-infrastructure technologies. This is a small price in relationship to the global economy, and the fact that failure puts the entire world in jeopardy.

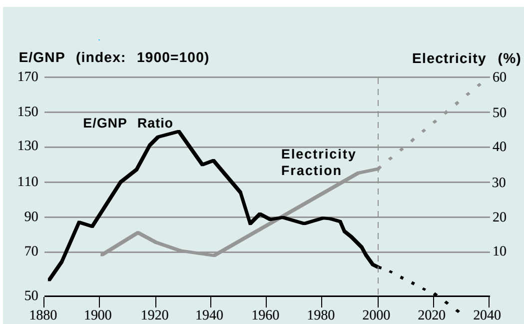
Electricity's Unique Role

Electricity has had a long history of stimulating and sustaining economic growth and improving the efficiency of all factors of production, particularly the productivity of labor and energy. The amount of energy required to produce a dollar of goods or services (the energy intensity of economic growth) is being reduced as the electricity intensity of the economy grows. As electricity's share of total energy increased from 15% in 1950 to nearly 40% in the U.S. today, the energy required per unit of GDP dropped by about

Prosperity and electricity use remain strongly correlated.

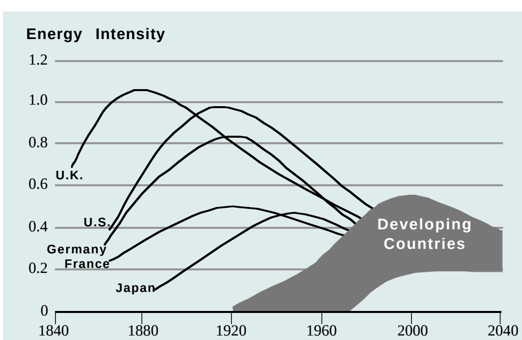


Using more electricity means using less total energy.



Source: Electricity in the American Economy, Sam H. Schurr, et al., 1990

Developing countries will be able to leapfrog over historic pathways of development using more efficient technologies.



Source: Scientific American, Sept.1990

one-third. The Roadmap participants see this trend continuing through the next century. In the next 50 years alone, U.S. energy intensity (E/GDP) is expected to drop again by about one-half, as electricity's share of total primary energy consumed approaches 70% through the technology opportunities envisioned in this Roadmap.

Advanced electrotechnologies also appear capable of enabling the developing nations to leapfrog over the historically less efficient development pathways taken by today's more affluent nations. These nations pursued a similar developmental trajectory, using increasing amounts of energy per dollar of goods and services in the initial stages of industrial development, then peaking, and then experiencing a steady decline in energy intensity, fostered in large part by electrification of their economy. Electrification introduces new efficiencies into the use of energy, labor, and capital for industry, business, and homes. Most important for the future, the peak for each nation has been successively lower, as each passes through the consecutive economic stages using more efficient technologies. Electrification and continued improvement in electrotechnologies are essential if the developing nations are to maintain this trend of accelerated resource efficiency in the global economy.

Electricity has been extended to over 1.3 billion people over the last 25 years, with leveraged economic impact. In South Africa, for example, for every 100 homes electrified, 10 to 20 new businesses are started. Electricity frees up human labor—hours per day spent in such marginal tasks as carrying water and wood—and it provides light in the evening for reading and studying. These simple basics can become the stepping stones to a better life and a doorway to the global economy. Electricity's unique capability to be effectively produced from a wide variety of local energy sources, along with its precision at the point of use, make it the ideal energy carrier for economic and social development. Moreover, using distributed electricity generation to achieve basic rural electrification goals in the developing world can help counteract the trend to massive urbanization. People in rural areas and villages need access to the opportunities and jobs that are now perceived as attainable only by migrating to large cities. Electrification should also help with efforts to improve deteriorating urban air quality in the growing mega-cities. Mortality from respiratory infections may be five times higher in developing countries than in developed countries. For example, the total health cost of air emissions in Cairo alone is now estimated to exceed $1 billion per year.

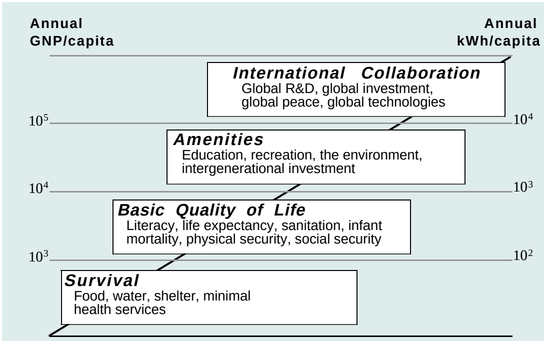
The Requirements for Sustainability

Achieving global sustainability without impeding the aspirations and progress of developing nations or hobbling today's industrialized nations will require the application of a new mix of highly efficient, affordable, and interdependent technologies to meet the basic requirements of sustainable development. These include at a minimum:

- **Human needs**—diffusion of innovative technology to ensure needed, adequate, and affordable food, shelter, security, and public health for a world of 10 billion people
- **Infrastructure**—technologies to improve the delivery systems for energy, communication, transportation, fresh water, and sanitation
- **Natural environment**—technologies to ensure clean air, clean water, arable land, and enhanced protection of forests, wetlands, biodiversity, and climate
- **Human environment**—technologies to enhance urban quality of life and access to education, information, and economic opportunity

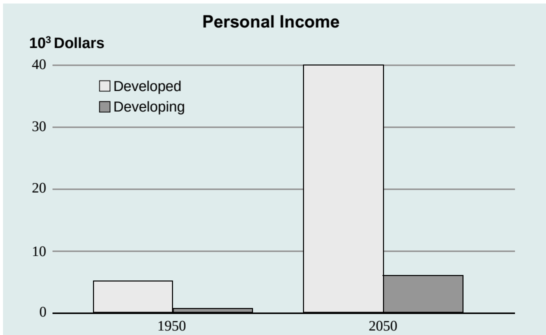
Paradoxically, the pathway to sustainability will involve transient environmental impacts by the world's poorest people as they develop economically to the level where they can

Priorities change as affluence increases.



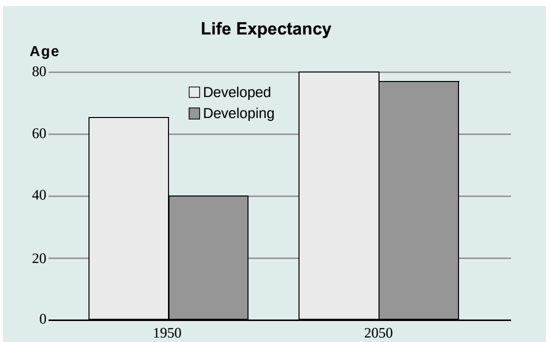
Source: Starr

The disparity in global income will continue to grow unless global development is accelerated.



Source: U.N. Development Project

The disparity in life expectancy is expected to close.



Source: U.N. Development Project

afford to divert significant resources to environmental protection. This notion is captured by Starr (1998) in his "four social categories," which characterize global society by per capita income and electricity consumption. A large majority of the world's population is now trapped in the bottom two levels, where the focus of everyday life is on survival and acquiring the basics now taken for granted in developed nations. Minimizing transient environmental impacts in achieving sustainability will depend on providing the technologies and institutional avenues that enable developing countries to grow rapidly out of poverty, reaching at least the "amenities" level where it becomes possible to devote a portion of income to environmental protection and intergenerational investment.

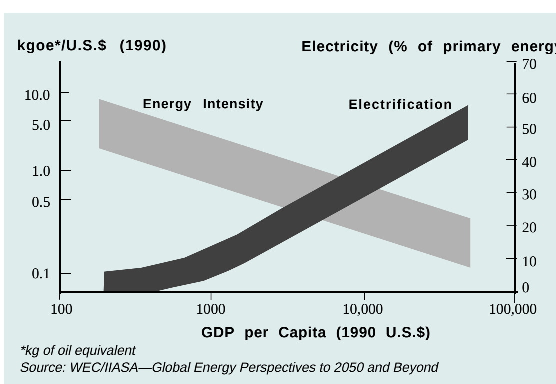
Roadmap participants believe that the alternative—constraining economic development in the most populous regions of the world to achieve singular environmental ends—is untenable and would have an increasingly significant, if not dominant, influence on global security and sustainability in the 21st century.

The Roadmap suggests that an essential part of the pathway out of poverty is ensuring a universal foundation of at least 1000 kWh/yr of electricity per capita. The difficulty of this task is compounded by the fact that 90% of the world's population in the next 50 years will be born into the survival and basic quality of life categories. Moreover, the workforces of Africa, Asia, and Latin America are projected to grow by more than 700 million over the next 20 years, adding an *increment* of workers equal to the *total* workforce of the industrial countries today. Failure to provide jobs and economic opportunity could create severe social and political problems, as well as added pressure for migration. A benchmark of concern is the widening gap between average and median global per capita income, despite the global economic expansion of the last 50 years.

Key Trends Toward Sustainability

A number of trends point toward a progressive decoupling of the world's economic development from depletion of natural resources, driven in large part by new and emerging capabilities of science and technology. Overall, the technologies of the future will be cleaner, leaner, lighter, and drier—or more efficient and less wasteful of materials and water. They will also be much more tightly integrated through microprocessor-based control, and will therefore use human and natural resources much more efficiently and productively. Energy intensity, land intensity, and water intensity (and to a lesser extent, material intensity) of both manufacturing and agriculture are already heading downward. They are not yet falling fast enough to offset the surge in population, but there is optimism that advances in science and technology through stepped-up R&D and prompt deployment of the results could accelerate these trends, helping to reconcile economic and environmental development in the coming century. Some of the well-established trends are discussed below.

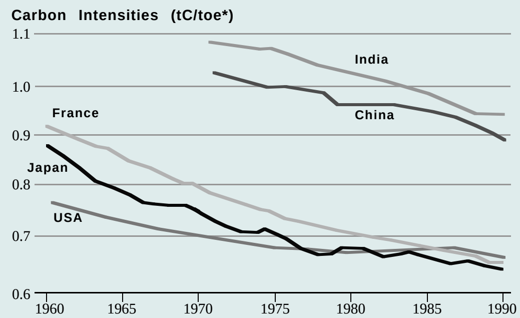
Energy intensity declines with greater economic development and electrification.



Energy Intensity

- Aggregate global energy intensity has been steadily declining by about 1% per year for the last 150 years. Electricity and the technologies it enables will increasingly be the primary factors in energy intensity reduction.
- Nevertheless, the efficiency of the full energy supply chain (i.e., fuel extraction, fuel transportation, energy conversion, energy delivery, end-use consumption) has today only reached about 5%; therefore, large opportunities for improving efficiency remain at every stage in the chain.

The decarbonization of energy in developing countries is following historical precedent.

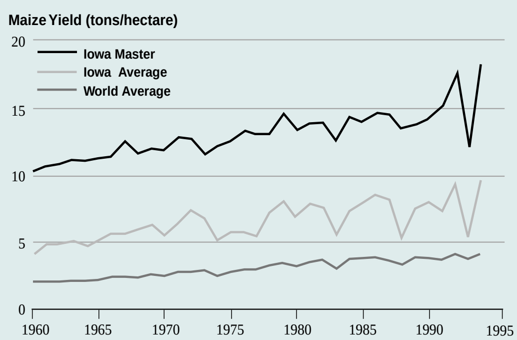


**Tonnes of carbon per tonne of oil equivalent*
Source: National Academy of Engineering, 1997

Decarbonization of the Energy System

- The global energy system has been decarbonizing at a rate of about 0.3% per year over the last 150 years, as the energy economy has moved from wood to coal to oil, gas, nuclear, and renewables. This has reduced carbon per unit of energy used (C/E) by about 40% since 1850.
- Aggressive development of advanced generation technologies can accelerate the 150-year trend of decarbonization, leading ultimately to a hydrogen/electricity-based global energy economy.
- Sustainability requires that global carbon emissions be reduced while growing the global economy. This will necessitate reductions over the coming decades in both energy intensity (at ~2% per year, or twice the historic rate) and carbon per unit of energy (at >1% per year, or more than three times the historic rate).

Bringing average world farm yields up to U.S. levels would free up agricultural land.



Source: National Academy of Engineering, 1997

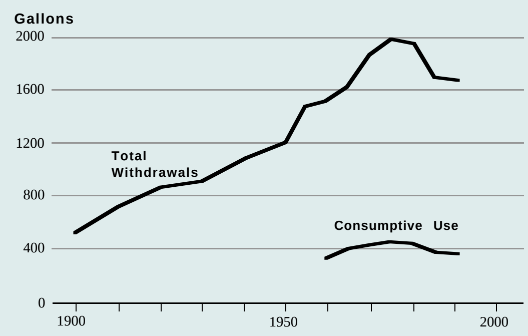
Land Use Intensity

- On a global basis, the land area used for agriculture has remained constant since 1950, despite doubling of the population. The stage is set to reduce it through technology advances.
- The primary reason for this expected decrease is the dramatic improvement in agricultural yields: since 1940, wheat yield in the U.S. has increased 300% and corn 500%, for example. Applying high-yield methods progressively in various parts of the world can begin to reduce land requirements. Further productivity gains are expected from ongoing research in crop genetics, as well as from the use of satellite imaging and distributed sensors and controls to enable precision farming.

• Farmland reduction has begun in some regions of the world. In the last 50 years, roughly 20 million hectares (50 million acres) of cropland have been reconverted to forests in the United States and Europe.

• If the global average agricultural yield can be brought up to today's U.S. average yield over the next 50 to 70 years (about a 1.5% per year improvement), the world could feed 10 billion people a 3000 calorie/day diet while sparing half of today's farmland. Thus, an area the size of Amazonia could potentially be reconverted to forest or alternative uses in the next half century. This has large-scale implications for water use and carbon sequestration as well.

Declining daily water usage per capita in the U.S. could be accelerated by diminishing agricultural requirements.



Source: National Academy of Engineering, 1977

Water Use Intensity

• Globally, fresh water availability has dropped from 20,000 cubic meters per capita in 1950 to 8000 cubic meters today as a result of population growth.

• Per capita water withdrawals in the United States increased by 2% per year from 1900 to 1970, but have dropped appreciably since 1975, and are now trending downward at 1.3% per year.

• Water intensity in U.S. industry peaked earlier, and has dropped even more sharply, from 14 gallons/GDP in 1940 to 3 gallons/GDP today.

• Large additional reductions are possible, particularly in light of the diminishing spatial requirements for agriculture. Agriculture currently uses about two-thirds of global water withdrawals.

• Advanced electrification can also provide cost-effective desalinization and purification, adding to available fresh water supplies.

Materials Use Intensity

• Economic growth in developed nations is moving toward nonmaterial-consuming economic activities, ranging from software to services. However, trends in economic "dematerialization" are equivocal so far. Material intensities (Mt/GDP) for heavier materials (e.g., steel, timber, copper, and lead) are all trending down, while material intensities for lighter materials (aluminum, plastic, and paper) are trending upward.

- Recycling is gaining ground. Recycling rates in North America, for example, are now approaching 65% for steel, lead, and copper, and 30% for aluminum and paper. Yet only about 1% of all materials consumed by the U.S. economy are converted into products that are still in use after a year.
- Over the long term, reclamation and remanufacturing are even more attractive than recycling. Whereas recycling moves value-added materials to a lower commercial value, reclamation returns usable components to the manufacturing chain. Remanufacturing is the most attractive pathway because it puts high-value-added items back into as-new condition. The trend toward leasing of products, with lifetime ownership retained by the supplier, is one manifestation of this emerging form of resource management.
- Nevertheless, product consumption in rich countries is still growing faster than dematerialization. As a result, per capita municipal waste is increasing in the U.S. by 1.6% per year. In the future, this trend can be at least partially offset by implementing industrial and urban ecology principles, facilitated by innovative electrotechnologies designed to improve efficiency, reduce wastage, and provide more precise process control.

The 2% Solution

The rate of innovation is particularly critical to sustainability. To support a sustainable future, Ausubel and other Roadmap participants have concluded that a "2% solution" is needed. By this, they mean that productivity improvements in a range of areas—including global industrial processes, energy intensity, resource utilization, agricultural yield, emission reduction, and water consumption—need to occur at a pace of 2% or more per year over the next century. If the advances are broadly distributed on a global basis, this pace should be sufficient to keep the world ahead of growing social and environmental threats. It will also generate the global wealth necessary to progressively eliminate the root cause of these threats, and provide the means to cope with the inevitable surprises that will arise. For example, a 2% annual increase in global electricity supply, if made broadly available in developing countries, would meet the goal of providing 1000 kWh per year to the 4 billion people in 2050 otherwise likely to be subsisting below that level under current trends in electrification.

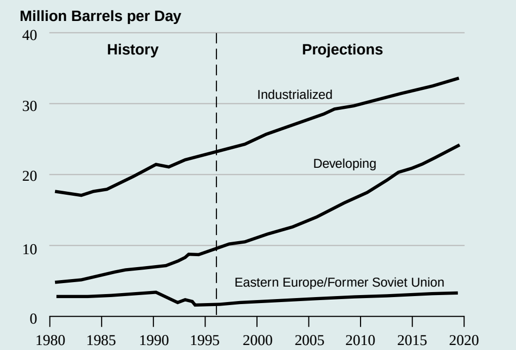
This pace will not be easy. It is in line with the cumulative advancement in the United States during the past century, but at least twice the world average over that period. The disparity has been particularly great in the last 25 years, as population growth has overtaken economic development in many parts of the world. The result has been massive borrowing to maintain or enhance short-term standards of living. In contrast, sustaining the 2% solution throughout the 21st century would allow essential global economic development while sparing the planet. The result should help stabilize world population (to the extent that wealth is a primary determinant of population growth), limit atmospheric levels of greenhouse gases below agreed-upon strategic limits, provide sufficient food for the bulk of the world's people (as well as the wherewithal to buy it), and return significant amounts of land and water to their natural states. Making this happen is in the enlightened self-interest of all the world's peoples.

Roadmap participants see technology and the spread of liberal capitalism as powerful agents for the 2% solution by fostering global development and enabling worldwide participation in market economies. However, participants registered some concern about unbridled opportunistic globalization overrunning local cultures and societies, creating instability, unrest, and conflict. At its worst, globalization could lock weaker nations into commodity-production dependencies, serving a global "survival-of-the-fittest" economy in which the rich get richer and most of the poor only stay poor. Establishing greater dialogue and cooperation among developed and developing nations is therefore considered critical to ensuring that globalization delivers on its promise as a vehicle of worldwide progress that honors the diversity of nations and peoples. The United Nation's "Dialogue Among Civilizations" initiative in the year 2001 is noted as a potentially powerful opportunity to begin creating the necessary framework for significantly enhanced global communications and cooperation in the new century.

The Need to Diversify Transportation Fuels

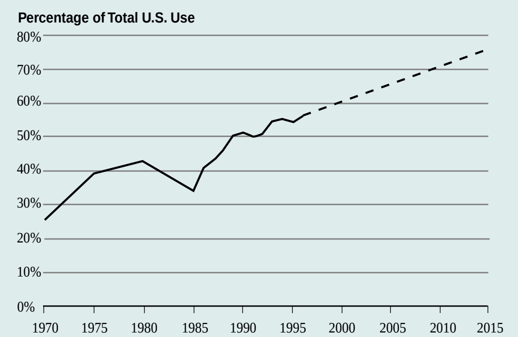
Economic development involves increased mobility. Transportation now accounts for 20% of global primary energy use, nearly all derived from petroleum. Sustainability demands not only more efficient transportation, but declining dependence on oil. In this context, electrified transportation is rapidly becoming a necessity, not just an option. Fuel diversification, which can be primarily achieved through the intermediary of electricity, will help moderate the global competition for petroleum as developing countries build their transportation systems. Electromotive propulsion options will also improve energy efficiency and reduce carbon emissions from transportation by at least a factor of two as technology advances.

Global competition for petroleum will intensify as developing countries build their transportation systems.



Source: *Energy Information Administration/International Energy Outlook 1999*

Oil imports could represent 75% of total oil use in the U.S. by 2015.

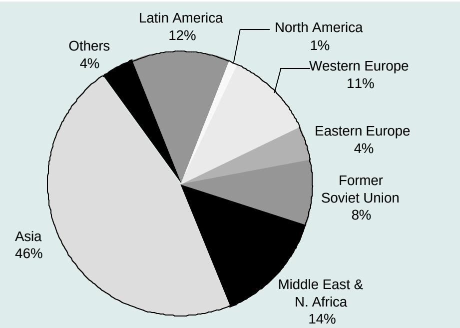


Source: *Energy Information Administration*

Considerable uncertainty exists regarding future global petroleum reserves, with estimates ranging from less than 50 years supply to more than 100 years. Nevertheless, the threat of oil production peaking in the next two or three decades, plus its uneven distribution, increases the risk of supply problems, particularly as the emerging economies in Asia, Latin America, and Africa rush to add at least 40 million bbl/day to global demand. Moreover, competition for the world's highly geographically concentrated petroleum reserves is likely to continue to foster global instability, distorting foreign and military policy over an ever-wider range of nations.

In contrast, electricity's future role in transportation looks particularly promising. The Roadmap participants conclude that by 2020, most new vehicles worldwide could be emission-free at the point of use. Electric, hybrid, and fuel-cell-powered vehicles should be competing aggressively in the market for personal transportation. Ultimately, hydrogen-fueled systems could provide a truly sustainable, zero-emissions surface transportation capability if necessary development priority is given. Self-guided vehicles may also become available to free up transportation time for work or leisure activities, revolutionizing the use of the automobile.

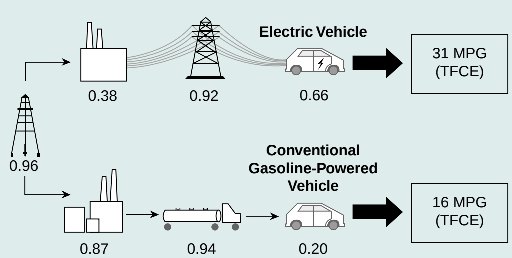
Developing countries will account for 2/3 of the growth in world oil demand in the next decade.



Total Incremental Demand = 43 x 10^6 bbl/day

Source: WEC, IIASA

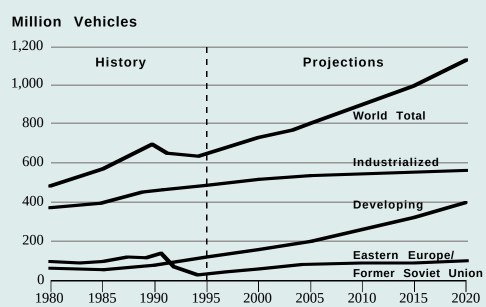
Electric vehicles are already about twice as energy efficient as their gasoline counterparts.



Moreover, the relationship between transportation systems and the electric power industry could be transformed by the development of fuel cell vehicles. A number of scenarios are possible, but depending upon the fuel infrastructure these electrically driven vehicles could become either net consumers of electric power or net suppliers to the electric grid. In the first case, the fuel used would be hydrogen produced by electrolysis at a central station (ultimately nonfossil) power plant, and reconverted by an onboard fuel cell to electricity to drive the vehicle. In the second case, the fuel used would be hydrocarbon-based and produced in a typical refinery operation; it would be delivered and stored in a manner much as used for today's gasoline-powered vehicles, and then converted by the onboard fuel cell to electricity to drive the vehicle. In either case, the vehicles take advantage of the high efficiencies possible not only with fuel cells but with electric propulsion itself. In one recent case, for example, a Toyota RAV-4 was converted to electric propulsion for the race at the American Tour de Sol in New England, and it proved to be 93% more energy efficient—using total fuel cycle efficiency (TFCE)—than its gasoline counterpart.

The Roadmap participants explored the growing potential for convergence between the transportation and electricity industries in the 21st century by considering a scenario where battery and fuel-cell electric vehicles (or other advanced equivalent technology) capture the new road vehicle market by 2050. Vehicles that run on batteries or hydrogen produced by electrolysis at stationary plants would require at least 10 x 10^{12} kWh per year of electric energy. Alternatively, fuel cell vehicles transforming hydrocarbons onboard could become mobile power sources, as well as transportation systems. These vehicles could be plugged in at home or the workplace to provide power during the 90% of the time that most are not on the road. If proven cost-effective, such vehicles could see widespread use, and generate enough electricity to reduce the requirement for new central station generation capacity by up to 20% through the year 2050. (These scenarios are described in greater detail in Appendix B.) Thus, the actual impact of fuel cell vehicles on electricity generation requirements will depend critically on whether the vehicle is a net buyer or seller of grid power, as well as on fuel markets and availability, environmental issues, and whether and how rapidly infrastructures are developed to meet the needs of the new generation of vehicles.

The number of vehicles on the road will exceed 1 billion by 2020.



Source: Energy Information Administration/International Energy Outlook 1999

For dense interurban corridors, high-speed, electrified magnetic levitation trains offer an attractive strategic alternative to less-efficient air travel. At the same time, local telecommuting is helping control urban congestion and time wasted in transit. And ultimately, "virtual trips" based on tele-presence technology are likely to substitute for an increasing part of the demand for physical transportation.

Technological Targets for Sustainability

With a strengthened electrotechnological foundation in hand by 2025, the world could be well on the path to economic and environmental sustainability by mid-century. There is no single measure of sustainability; rather, it will require continued progress in a wide variety of areas that reflect the growing efficiency of resource utilization, broad improvements in the quality of life for today's impoverished people, and acceleration of the historical shift away from resource-intensive economic activity. Table 6-1 provides a first-order approximation of what sustainability will require. In many cases, the targets represent a significant stretch from today's level; but they are all technologically achievable.

Sustainability tomorrow requires our urgent commitment today.

The vision and commitment needed to achieve global sustainability must include widely shared support for the role of technical innovation in meeting pressing human needs. The Roadmap's goals for sustainability are simply too far reaching to be achieved solely through governmental policy or directives. Rather, they will evolve most quickly from a healthy, robust global economy in which accelerated technological innovation in the private sector is fostered and supported by the public sector.

It is encouraging that economic development is being increasingly facilitated by technologically driven dynamics, faster information flow, and worldwide financial markets. Every day, approximately $1 trillion moves across international borders. International trade is growing twice as fast as world production, and overseas investment is increasing at least twice as fast as trade. These market mechanisms must be steadily expanded to foster rapid and universal diffusion of the latest technology into the developing nations in return for the goods they produce and the empowerment of all people to participate in economic development and global market expansion.

An even more basic need underscored by the Roadmap participants is a global institutional framework capable of attracting capital to the points of greatest need and opportunity. Essential to this vital flow is the universal guarantee of the rule of law, readily interpretable and supported by judicial recourse. Economic and environmental sustainability in the 21st century will also require an expanded and enduring vision of global partnership, mutual dependency, and responsibility, a viewpoint that reaches around the world, through all spheres of human activity, and across multiple generations. Decades of patient, determined commitment and collaboration by both public and private sectors will be required. As the distinguished British statesman Edmund Burke reflected over 200 years ago:

> *The state is more than a partnership agreement in the trade of pepper and coffee, calico, or tobacco…It is a partnership in all science; a partnership in all art; a partnership in every virtue and in all perfection. As the end of such a partnership cannot be obtained in many generations, it becomes a partnership not only between those who are living, but between those who are living, those who are dead, and those who are [yet] to be born.*

Burke's world was smaller and states less interdependent than in today's global economy. For a sustainable world in the 21st century, Burke's noble vision of "the state" broadens to include all people's shared responsibility for stewardship of the global future. We at EPRI and our many partners in this Roadmap venture are committed to that responsibility, and we invite you to join us.

Table 6-1 Sustainability R&D Targets	
Technology Area	**Sustainability Targets for 2050**
Infrastructure	Ensure universal availability of fresh water, sanitation, commercial energy, and communications. Provide streamlined infrastructure technology for worldwide urban use.
Electrification	Achieve universal global electrification (including at least basic electricity services of ~1000 kWh/person/year).
Energy intensity	Accelerate the rate of decline in energy intensity from 1%/year to 2%/year.
Energy efficiency	Double the efficiency of the entire energy chain, from 5% to 10%.
Decarbonization	Triple the rate of decarbonization of global energy, from 0.3%/year to 1.0%/year by 2030 and maintain.
Land use	Increase global average grain yields by 2%/year, and return at least 1/4 of global cropland to natural state or managed use.
Water use	Cut agricultural and industrial water use in half.
Transportation	Electrify >50% of global transportation.
Industrial ecology	Reduce industrial waste streams to near zero and minimize the need for virgin resources.
Education	Provide universal access to education and technical training.

Appendix A

Roadmap Participants to Date

Acknowledgments

EPRI's Research Advisory Committee provided guidance and support throughout the roadmapping process. The Roadmap has benefitted greatly from their review and critical comments, and we gratefully acknowledge their contribution. In addition, the development of the initial version of the Electricity Technology Roadmap would not have been possible without the participation and patience of a large number of electricity industry stakeholders from the private sector, academia, and government. We are indebted to all the Roadmap participants for their insights and constructive support. Their diverse views contributed to this synthesis; however, their participation does not necessarily represent unqualified endorsement of the report. We look forward to continuing to work with them as well as other stakeholders in extending the vision and pathways of this Roadmap Initiative.

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Appendix B

Alternative Future Scenarios

The Roadmap exploration of energy futures began with consideration of the scenarios developed by the International Institute for Applied Systems Analysis (IIASA) for the World Energy Council (WEC), as described in the report "Global Energy Perspectives" (1998). However, the WEC scenarios do not reflect the higher levels of electrification and energy conversion efficiency that the Roadmap participants expect will be needed to enable global economic growth while protecting environmental values and conserving natural resources. Consequently, the Roadmap team developed an alternative scenario for the energy system of the year 2050 that would facilitate reaching the Roadmap destinations.

This Appendix summarizes the WEC scenarios and compares them with the Roadmap-derived alternative.

The WEC defines three basic cases, reflecting high economic growth (Case A); an evolution of current trends (Case B); and high environmental and policy constraints (Case C).

WEC Case A: High Economic Growth

Case A emphasizes economic growth. It is technology and resource intensive. Growth provides the resources to turn over capital stock rapidly, so that the scenarios are characterized by continuing commercial access to the latest technology developments. Case A is divided into three scenarios that are very similar in their end-use energy patterns, but differ in their energy supply structures.

Scenario A1 is driven by the continuing availability of gas and oil, and to a lesser degree coal, with few additional controls on utilization. Fossil resources provide 66% of primary energy in 2050 and by 2100 have only declined to 50%. Total primary energy consumption is ~25 Gtoe in 2050 and ~45 Gtoe in 2100.

Scenario A2 reflects conditions in which oil and gas availability is low and prices are high. As a result, the world becomes increasingly dependent on coal. Coal consumption grows from 25% of primary energy in 2000 to approximately 32% in 2050 and nearly 40% in 2100. A vigorous coal generation research program would be needed in this scenario to reduce the costs of coal production from increasingly less-accessible deposits and to develop and commercialize new methods for coal conversion, including the production of methanol, hydrocarbon liquids, and chemicals in addition to syngas.

In contrast, **Scenario A3** provides the same primary energy levels with a supply mix that is only 25% fossil-based (and declining rapidly) by the end of the 21st century. Large-scale implementation of nuclear power, solar, biomass, and other renewables provides the bulk of primary energy in this scenario, and sets the stage for a post-fossil-fuel age.

WEC Case B: MIddle Course

Case B, represented by a single scenario, is a middle course with modest rates of economic growth, technology advancement, energy demand, and environmental regulation. It has many features of the current status quo. It is likely to take form as a gradual evolution from current conditions. The Case B scenario appears to be achievable without relying on significant improvements in current institutions, technologies, and estimates of the availability of fossil fuel resources. Energy supply and use patterns remain closer to current conditions for a longer time period in Case B than in either Case A or Case C. In the longer term, Case B may lead to increasing fuel extraction costs and a decline in the availability of high-quality fuels. These factors may in turn cause significant price increases for some fuels, with resulting shifts in primary energy portfolios.

WEC Case C: Ecologically Driven

In Case C, stringent environmental policies worldwide emphasize improvements in both supply-side and end-use efficiency. Aggressive targets for lower carbon emissions lead to global restrictions on the use of fossil fuel (which declines to less than 20% of primary energy by 2100). When coupled with lower energy consumption, global carbon emissions in 2100 are a factor of 10 smaller than in the high-coal-use scenario A2, for example. Case C is divided into two scenarios that emphasize gas and oil through the middle of the 21st century, followed by a transition to a renewable basis (in Scenario C1) or to a nuclear/renewable basis (Scenario C2).

Roadmap Goals for Accelerated Electrification

The WEC scenarios were used as a point of departure for considering additional scenarios that illustrate the societal value of universal electrification to enhance efficiency and as an "equal opportunity enabler" of all primary energy sources. As described in Chapter 6, the Roadmap sustainability destination proposes a universal minimum electricity consumption of 1000 kWh per person per year and an average per capita electricity consumption of 3000 kWh per year in what is now considered to be the developing world. This Roadmap sustainability destination will require about 10,000 GW of electricity generation capacity by 2050, producing approximately 60 trillion kWh/yr. Stated in terms of the WEC scenarios, the Roadmap targets electricity consumption ~50% greater than the WEC economic growth scenarios (Case A), but results in a total primary energy consumption only about 20% larger than the ecologically driven scenarios (Case C). Additional details on this Roadmap scenario are provided in Table B-1. The scenario is also compared with the WEC scenarios in Table B-2.

The Roadmap-derived scenario is designed to meet the need for abundant, low-cost energy while improving energy supply security and addressing environmental concerns by emphasizing energy efficiency. To meet these needs, the Roadmap scenario features a broad portfolio of generation and delivery technologies, utilizing all available fuel sources (implying the availability of proven technologies, financial resources, and a willingness to invest in the electricity infrastructure).

These goals carry some important implications for the technology elements of the generation portfolio, including:

- The need for breakthroughs in the performance and cost of solar photovoltaic technology, achieving at a

Table B-1 Global Trends and Roadmap Goals	1950	2000	2020	2050
Population (billion)	2.5	6.2	8	10
Gross world product (trillion 1990 $US)	4.3	32	50	100
Per capita income (1990 $US)	1,700	5,200	6,200	10,000
Primary energy (Gtoe)	1.5	10	13	17
Energy intensity (toe/$10^3$$)	0.35	0.31	0.26	0.17
Electricity fraction of primary energy (%)	20	38	50	70
Electricity share of primary energy (Gtoe)	0.3	3.8	6.5	12
Electricity conversion efficiency (%, global average)	28	32	40	50
Electricity final energy (Gtoe)	0.08	1.2	2.6	6
Electric generating capacity (thousands of gigawatts)	0.2	3	5	10
Capacity factor (%, global average)	50	50	60 *	70 *
Electricity consumption (trillion kWh)	1	13	36	60 **
Per capita electricity consumption (kWh/yr)	400	2,100	3,500	6,000

**For central station generation*
***Includes 10 x 10^{12} kWh for transportation*
Sources: UNDP, WEC, DOE/EIA, EPRI analysis

minimum 25% conversion efficiency at an all-in cost of $50/m^2 (area of the PV modules plus supporting structure and interconnections) by the year 2020.

- The need for breakthroughs in nuclear power generation, achieving conversion efficiencies of >50% by 2050, at a cost that is comparable with that of other generation technologies (projected to be ~$50/MWh in 2050).
- The need for continued reduction in the cost of coal-based generation, combined with improvements in conversion efficiency to >60%, reduced environmental impact, and the availability of low-cost carbon sequestration technology. The latter is deemed necessary both to reduce greenhouse gas emissions and to reduce the risk of investing in coal-based generation plants.

These and other technology advances are particularly important, because they illustrate the means by which technologists and policy makers can accelerate the development of the universal electricity infrastructure essential to sustainable economic growth.

Table B-2 Summary of WEC Scenarios and Roadmap Goals										
Scenario	**Drivers**		**Primary Energy 2050 (Gtoe)**	**Energy Intensity 2050 (toe/ 10^3\$)**	**Energy Mix 2050** %					**Carbon Emissions (Gt/yr)**
					Coal	**Oil**	**Gas**	**Nuclear**	**Renewables***	
A1	High growth, plentiful oil		25	0.22	15	32	19	12	22	11.6
A2	High growth, coal emphasis		25	0.22	32	19	22	4	23	14.7
A3	High growth, transition to post–fossil fuel age		25	0.21	9	18	32	11	30	9.3
B	Moderate growth		20	0.23	21	20	23	14	22	9.6
C1	Ecologically driven, nuclear phaseout		14	0.16	11	19	27	4	39	5.3
C2	Ecologically driven, nuclear renaissance		14	0.16	10	18	23	12	37	5.1
Roadmap Scenarios	**High growth, rapid electrification, reduced resource intensity**	**High Coal**	**17**	**0.17**	**30**	**10**	**30**	**15**	**15**	**9.6**
		High Renewable/ Nuclear	**17**	**0.17**	**10**	**10**	**40**	**20**	**20**	**7.2**

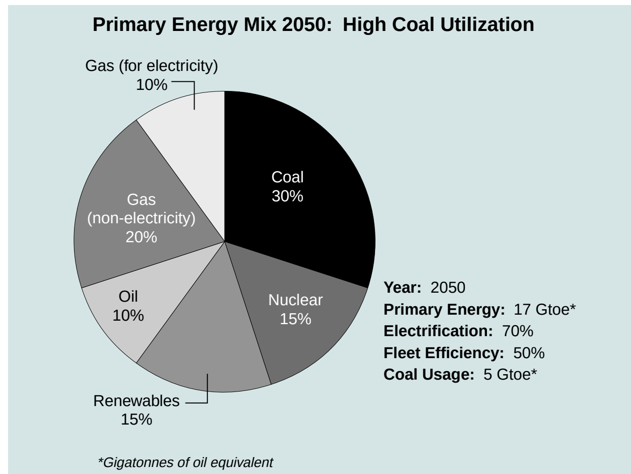
**See sidebar comparing the WEC and Roadmap scenario energy mixes*
Sources: A, B, C from WEC, IIASA; Target from EPRI and Roadmap participants

COMPARING THE WEC AND ROADMAP SCENARIO ENERGY MIXES

Analyses of energy mix scenarios frequently differ in the method used for comparing the primary energy contributions of the various power generation technologies. The treatment of primary energy associated with renewables poses a particularly difficult analytical problem. The energy mixes for the Roadmap scenarios in Table B-2 were developed using the "direct equivalence method," which assumes the primary energy for renewables to be the same as the electricity generated from the renewable resource. While not completely accurate, this method allows a relatively straightforward comparison of the primary energy resource requirements of the different generation technologies. In addition, it's an appropriate choice for the Roadmap analysis, given the focus on resource sustainability and the fact that the renewable energy input to the electricity conversion is not "consumed" in the same sense that fossil fuel resources are consumed in the process of electricity generation. In contrast, the WEC scenarios use the "substitution equivalence method," in which primary energy equivalents for nonfossil generation are calculated using an assumed conversion efficiency of 38.6%. This approach has the effect of inflating the renewables contribution relative to the other elements of the generation mix. To allow for direct comparison of the WEC and Roadmap scenarios in Table B-2, recalculation of the Roadmap renewable contribution using the substitution equivalence method would be needed. This would have the effect of approximately doubling the renewable contribution of the Roadmap scenario and would have corresponding ripple effects in the percentages for the other energy sources.

As shown in Table B-2, the Roadmap high electrification scenario is compatible with a range of fuel and primary energy portfolios. One example is a high-coal scenario, in which countries with large coal reserves depend on them to meet their energy needs while adding to their energy security. Considering anticipated improvements in the environmental performance of coal-based generation and the development of low-cost carbon sequestration options, this scenario can accommodate up to a doubling of world coal use from 2.5 Gtoe in 2000 to 5 Gtoe in 2050. At the same time, natural gas utilization could increase to as much as 5.2 Gtoe, up from 2.2 Gtoe in 2000. Petroleum usage would be able to decline from 4.0 Gtoe in 2000 (40% of world primary energy use) to as little as 1.7 Gtoe in 2050 (10% of primary energy). A sharp reduction in oil usage would reflect a growing concern over urban and regional pollution caused by internal combustion engines, coupled with energy security considerations and the availability of new technologies, such as coal-based liquid fuels and an array of electricity-based transportation alternatives. In fact, this scenario anticipates ~50% displacement of petroleum by higher-efficiency, electricity-based propulsion in the transportation sector. Additional information on transportation impacts on energy usage can be found later in this Appendix.

Nuclear power and renewable energy systems are anticipated to make important contributions to the energy mix—at least 15% of primary energy each in the year 2050, or a total energy of nearly 5 Gtoe. This expectation is based on successfully addressing public safety concerns about the safety and reliability of new nuclear plants, and achieving significant performance and cost improvements for renewables. The carbon emissions for this portfolio are approximately 9.6 GtC per year in 2050, with the expectation that carbon emissions will



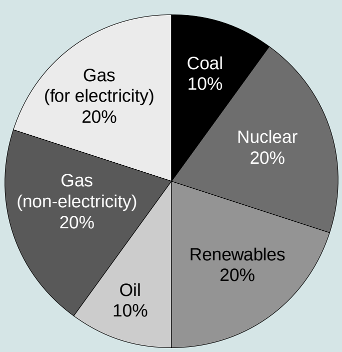
trend steadily downward in the latter half of the 21st century as renewables and nuclear power assume progressively larger fractions of total electricity generation.

Other primary energy portfolios that are much less coal- and fossil-intensive are also capable of meeting the goals of the Roadmap sustainability destination. As one example among several, a low-coal, higher renewable and nuclear scenario could see coal usage decline by approximately 40% over the period 2000–2050, as illustrated in Table B-2, without affecting the overall electricity production or the electricity fraction of primary energy. The carbon emission rate for this portfolio in 2050 is approximately 7.2 GtC per year.

The intent in describing these scenarios is not to forecast future energy use, but to show that the high electrification and high efficiency of the Roadmap destination enables the greatest flexibility in primary energy mixes while facilitating both accelerated economic development and resource efficiency.

The actual fuel and generation portfolio will depend on economic, political, and environmental conditions, as well as on the development and successful commercialization of new technologies. For example, dramatic improvements in the cost/performance characteristics of solar photovoltaic devices could completely change the economics of renewable power generation, resulting in a substantially different generation mix. From a research planning standpoint, the uncertainty regarding the future mix indicates the need for a portfolio of technology development projects that covers the known and anticipated technology gaps and is robust enough to handle unpredictable future geopolitical, business, and policy environments.

Primary Energy Mix 2050: High Renewable/Nuclear Generation



Year: 2050
Primary Energy: 17 Gtoe*
Electrification: 70%
Fleet Efficiency: 50%
Coal Usage: 1.6 Gtoe*

**Gigatonnes of oil equivalent*

Both the Roadmap scenario and the WEC scenarios recognize the growing importance of higher quality fuels and energy systems to provide greater flexibility at the point of use. The Roadmap follows this trend to its logical conclusion by focusing on electricity, the most flexible and efficient energy form.

This focus on electricity places the Roadmap scenario at a misleading disadvantage with respect to one frequently used measure of the efficiency of an energy system, the ratio of final energy to primary energy. Here, *primary energy* is defined as the energy content of the original resources—coal, oil, gas, uranium, etc. *Final energy* is the energy available at the point of use—gasoline in the fuel tank of a car; the electricity for powering a room air conditioner. The final/primary energy ratio for non-electric technologies will often be higher, even though the end-use appliance (e.g., a gasoline-powered automobile) has a relatively low energy efficiency. In contrast, the final/primary energy ratio of electrotechnologies will often be lower, but the end-use efficiency higher. In fact, consideration of the efficiency of the entire energy chain, in terms of primary energy per unit of GDP, almost always favors electricity.

Looking beyond just the final/primary energy ratio is therefore particularly important in evaluating the Roadmap scenario. In the final analysis, the much more meaningful goal is to achieve the highest economic productivity with the lowest consumption of primary energy, and the greatest flexibility in the resources utilized.

Energy for Transportation

The importance of transportation as a component of the energy portfolio results from the large amounts of energy involved, the low efficiency and environmental impacts of internal combustion engines, and growing energy security considerations related to oil. Currently, approximately 20% of global primary energy (or 2.0 Gtoe/yr) is used for transportation, and almost all of this energy is derived from oil. The Roadmap scenario assumes that the transportation portion of primary energy will remain constant at about 20% through 2050, while total primary energy use increases from 10 Gtoe to 17 Gtoe.

In the Roadmap scenario, the efficiency of all transportation systems is expected to increase dramatically during this period. By 2050, most vehicles will probably rely on electricity in some form, such as batteries, fuel cells, or various hybrid configurations involving these and others such as flywheels or ultracapacitors. With targeted efficiency increases in both electricity generation and these transportation technologies, the total fuel cycle energy efficiency of road vehicles could increase by as much as a factor of four by 2050. The overall energy efficiency of non-road transportation, comprising air travel, mass transit, and off-road mobile sources (about 25–30% of total transportation energy use), is likely to improve similarly on average. This means that although the amount of transportation service (measured in passenger-miles, for example) may grow manyfold over this period, primary energy for the transportation sector would increase by a much smaller factor.

The primary energy portfolio for transportation will also likely diversify over the next 50 years, shifting from oil dependency to a mixture of resources including oil, natural gas, and electricity, with the latter in turn drawing upon fossil, nuclear, and renewable primary energy resources. Environmental drivers and energy supply security considerations are likely to influence the changes in transportation's primary energy mix. The Roadmap scenario therefore assumes that oil's share of the transportation market will decline to about 50% by the year 2050.

The U.S. DOE's Energy Information Administration has the 2020 global road vehicle population at about 1.1 billion, about 50% above the current level. That fleet will continue to grow at an accelerating rate, as global living standards rise. By 2050, as many as 2.5 billion vehicles could be on the road. Some vehicles will be powered by electricity from the grid, either directly and stored in batteries or indirectly through electrolytic hydrogen production. Fuel cell vehicles can also be designed to operate on gasoline or diesel fuel derived from petroleum, methanol derived from natural gas, or hydrogen derived from chemical processing of coal, natural gas, or renewables.

Fuel cell vehicles that run on gasoline or methanol could be used to generate electricity while the vehicle is stationary and supply it to the grid. The number of vehicles that will be available to provide power to the grid is highly speculative, as is the time they will actually be "hooked up" and delivering power. As an example, assume that 200 million vehicles, each generating at an average rate of

25 kW, deliver this power to the grid for an average of 2000 hours per year. For these assumptions, the total energy delivered will be about 10 x 10^{12} kWh, or about 15% of the projected total worldwide electricity consumption in 2050. This amount of electricity could also be supplied by fewer vehicles generating at higher rates and/or more hours, as long as fuel storage requirements can be met either onboard or at the point of stationary use.

In contrast, both battery-powered and fuel cell vehicles running on electrolytically derived hydrogen will likely receive and store energy from the electricity grid. These vehicles could, in principle, use grid-produced electricity to store in batteries or as hydrogen during off-peak periods and sell the power back to the grid during power peaks as already described. However, the normal mode of operation of these vehicles is assumed here to be transportation, not power generation. To estimate the stationary electricity generation requirements, assume that the remaining 2.3 billion vehicles in 2050 each travel an average of 15,000 miles per year at about 0.20 kWh/mile. Including an allowance for increased use of advanced freight and mass personal ground transportation, these assumptions yield a total annual electric energy requirement of approximately 10 x 10^{12} kWh, or again about 15% of global electricity consumption.

As the above example shows, these different modes of EV operation—using power from the grid to power some of the electric vehicles and selling power to the grid from the other (fuel cell) EVs when parked—tend to offset each other in terms of electricity supply requirements. The actual net effect is difficult to forecast. It may hinge on factors such as the ability to create an infrastructure for generating, transporting and handling hydrogen safely and at reasonable cost. The Roadmap is based on the assumption of success in creating an electricity/ hydrogen infrastructure. This leads to an increase in capacity factor at stationary power plants. However, the concept of selling power from fuel cell vehicles to the distribution grid could have a significant market potential. The result would be an increase in mobile distributed generation and a corresponding decrease in the need for stationary capacity.

These scenarios should be treated as preliminary assessments of the potential impact of the electrification of transportation in the next half century. They involve a great many assumptions that can and should be challenged in future Roadmap workshops. As the electricity and transportation industries converge, the scale of the potential impact is large and warrants a much broader discussion of issues and points of view. These scenarios are put forward in the spirit of providing a point of departure for future discussions.

Appendix C

Roadmap Module Summaries

Power Delivery Module

This module is focused on ensuring a superior power delivery system to support the economy of the 21st century. Its vision is to transform the traditional power delivery system into a smart network that can facilitate the transition to a competitive marketplace for electricity, meet the reliability and power quality requirements of a digital society, and open the door to a revolution in customer services.

Conclusions and Recommendations

- New technologies, including Flexible AC Transmission Systems (FACTS) and superconducting cables, will enable the integration of the North American power grid under a single control regime, as well as establish the potential for major intercontinental power transfers from resource-rich regions of the world to concentrated population centers, and from low-cost regions to high-cost regions.
- High R&D priority is placed on lowering the cost of FACTS controllers and developing high-temperature superconducting cables (HTSC) with a power-carrying capacity several times that of ordinary cables. Advanced boring technology to put the HTSC cables underground is also needed.
- New technologies, including Custom Power controllers, DC networks, and advanced distribution automation, will meet the increasing need for premium power by precision manufacturing industries, financial institutions, information centers, and critical care facilities, among others.
- R&D priority is placed on lowering the cost of Custom Power devices and AC/DC converters, as well as introducing advanced distribution automation systems, capable of new functions using advanced sensors and software.
- Advanced meters with two-way communications capability will become the cornerstone of a competitive retail electricity market. Customer preferences for choice, convenience, and price will lead to real-time pricing options and an array of energy/information management services. More sophisticated interface technologies will facilitate integrated utility services, including telecommunications, information, entertainment, gas, and water.
- Development of affordable advanced metering and related sensor technology is a top-priority area for R&D.
- A major regulatory hurdle that could impede development of a smart power delivery system is uncertainty over how system owners and operators can recover investments in new technologies and in the R&D required to produce and sustain them. Establishing the necessary recovery mechanisms will require policy clarification at both federal and state levels.
- Investment in new power delivery technologies and related R&D could also be impeded by uncertainty over whether emphasis should be placed on upgrading conventional facilities or accelerating introduction of distributed resources (DR). Critical decisions need to be made concerning recovery of transmission system

investments stranded by DR and encouragement of distribution system investments related to the safety and VAR-support requirements of DR.

- Achieving widespread use of advanced power system controllers, such as FACTS and Custom Power devices, will require significant reduction in the cost of the underlying power electronics technology. Cutting costs by roughly one-half will require the use of new, wide-bandgap semiconductor materials—such as silicon carbide, gallium nitride, and thin-film diamond. Introducing these materials will require broad interdisciplinary, multi-industry collaboration.

Electricity Supply Module

The focus of the supply module is to identify critical areas of R&D that can shorten the time for bringing promising electric generating technologies from concept to commercial application. Its vision is to build a robust portfolio of clean, low-cost technologies that have the capacity and flexibility to meet diverse global needs for electricity over the next half century.

Conclusions and Recommendations

- The main drivers of electricity supply technology will be the environment and economic development. Given population and economic growth projections, the world will need some 10,000 GW of new capacity by 2050 (this figure includes replacing the existing fleet of 3000 GW). This is the equivalent of building a 1000-MW power plant every one or two days for the next 50 years.
- The environmental issue with the greatest potential impact on the energy sector is global climate change. Capping atmospheric concentrations of carbon at 550 ppm means that much of this new capacity must be carbon-free, and that the fossil fleet average efficiency must rise to 50%.
- The scale of expansion is unprecedented. The world will need all the energy sources it can get. Fuel diversity has value for both the near term and the long term.
- The path from 2000 to 2020 is primarily evolutionary. The developed world will largely meet the need for additional capacity with gas-fired combustion turbines. The developing world will continue to rely upon indigenous resources where feasible, most particularly coal in the case of China and India.
- The path from 2020 to 2050 is more of an opportunity for significant shifts in supply, based upon advanced technology. There is sufficient time for capital turnover and for technical breakthroughs to have large-scale impact.
- Continuing to push the efficiency of gas turbine technology is a high priority because it will be a key component in every advanced combustion technology system. Efficiencies are now eclipsing 60%, with enough momentum to reach 70%. In the 2020–2050 timeframe, combining gas turbines with fuel cells could push the efficiency to 80%.
- Fuel cells are receiving lots of development money, in part because of the potentially lucrative crossover from transportation to stationary systems.

- By 2020, advanced coal systems built upon gasification (syngas) platforms could be cost-competitive.
- Nuclear's primary research objective is to develop a cost-effective deployment option by 2020, perhaps earlier, based upon passive design. A deployment option means that a plant competitive with coal and gas will have been built and demonstrated by 2020, with the waste management program functioning.
- Renewables are suitable for extensive global development. Wind, due to its low cost, and photovoltaics (PV), due to its broad applicability, public acceptance, and technical potential, are foreseen as the dominant options. Thin-film PV costs are estimated to fall to $1.10/W in 2020, and $0.90/W in 2030 based upon current technology. But given the pace of development in the material sciences, fundamental technology breakthroughs are possible, resulting in increased conversion efficiency and lower cost.

Environmental Knowledge Base Module

This module describes opportunities for reducing the uncertainty of the environmental and health effects of electricity and other technologies, and for using an improved understanding of environmental issues to improve policy decisions. Its vision is to identify emerging environmental issues; understand their scientific, economic, and social aspects; define approaches for reducing the threats posed by these issues; and communicate the results to policy makers, the scientific community, and the general public.

Conclusions and Recommendations

- The most urgent current R&D needs include global climate change, air quality, electric and magnetic fields, and land and water contamination. These are all being addressed at some level.
- The highest priority area is climate change, because of the huge potential cost to society, especially if large near-term reductions in greenhouse gas emissions are deemed necessary, and because of the long-term risks associated with an unconstrained rise in atmospheric greenhouse gas concentrations. Work is needed to advance the state of the sciences relating to the causes, effects, and mitigation of climate change, and integrated analysis of the balancing of control costs against those of the effects of climate change. A technology strategy is also needed to identify and evaluate options for moving away from CO_2-emitting power production systems and fossil-fueled transportation systems.
- Air quality issues center around the effects of fine particles and tropospheric ozone. Key science needs include an improved understanding of the formation of the health-relevant particles; human exposure to atmospheric gases and particles as well as the health impacts of those exposures; and the spread of ozone and its precursors from sources.
- Although substantial progress has been made in demonstrating that EMF health effects are less than previously conjectured, considerable work is needed to bring this topic to confident closure.
- Issues involving complex trade-offs among sometimes competing forces are becoming increasingly important.

Improved tools for performing integrated assessments of such situations are needed to handle the growing complexity of the interactions between economic webs and environmental systems.

- New electricity technologies and systems will generate new environmental issues in the future. A robust capability for gaining an understanding of the potential environmental effects of emerging technologies will pave the way for their acceptance and broad implementation.
- Looking closer at electricity and its impacts, important issues that affect regional and local communities are revealed as topics for research. Participants in the new industry will become increasingly involved in regional and local community-based initiatives, with important environmental implications.
- No industry will prosper without the understanding, knowledge, and support of the public. In the area of environmental knowledge, education issues span childhood, adult, and industry professional needs.

Economic Growth Module

This module focuses on R&D needs and knowledge gaps that can be bridged by new electric technologies in all end-use sectors. It aims to exploit the advantages of electricity to foster economic growth into the 21st century. Its vision foresees that new electric technologies will continue to be an agent of progress for innovation in all sectors of the economy, from manufacturing to agriculture, services, communications, and transportation. In the long run, they will transform some sectors and even create new enterprises we can only dream about.

Conclusions and Recommendations

- Electricity will continue to steadily grow as a fraction of total energy use in the U.S. and worldwide. U.S. growth has been remarkably constant since 1960, averaging 75 billion kWh/yr.
- Module destinations were selected to reflect the future impact of technology innovation in the end-use sectors. These destinations are Productivity, Product Innovation, Business Practice, Energy Efficiency, and Environmental Quality. Feedback from interviews demonstrated the importance of these destinations. As emphasized by a chemical industry manager, "Using advanced process controls and sensors, we have driven our labor costs way down. Productivity has gone way up. The chemical industry is continuing to automate, but there is still much room for improvement. We aren't anywhere near optimal." A turbine industry executive pointed out, "Energy efficiency is a key goal of our industry. We will be supplying a wide range of small gas turbines for industrial and distributed generation applications, with efficiencies of 40% or better."
- The relationship between technology and market structure is critical. The work identified a series of social, economic, and environmental drivers and barriers. Technology policy must be designed to reflect demand pull, rather than simply supply push.
- Recognizing the breadth and depth of the module context, the concept of technology platforms was adopted to support a crosscutting approach to technology development. Six such platforms were identified: Materials Technology, Sensors Technology, Systems

Infrastructure, Model-Based Systems Technology, Information Technology, and Utilization Processes and Advanced Systems. These platforms were selected based on interviews and workshops with experts, as well as on their potential importance to a broad range of businesses. Follow-on workshops may be valuable in defining detailed technology needs and developing networks of potential collaborators.

- Development of new electric technologies will in most cases require collaborations among the industries that will most benefit from the technology. A significant effort is needed to identify potential partners. In this context, the Roadmap and its technology platforms emerged as an important tool in identifying industries for potential collaboration in development efforts.
- Communication of Roadmap results to policy makers emerged as an important follow-on to the definition of technology opportunities, as did education of end-use customers and the general public in the growing importance of electricity.

Sustainability Module

This module is focused on understanding the barriers, incentives, and approaches to a sustainable future. Its vision is of creative people and institutions fostering the availability, awareness, and acceptance of liberating technologies for the benefit of present and future populations. In line with this vision, the participants emphasized that:

- Imagining and striving for a sustainable future are crucial objectives for society
- Providing sufficient energy represents a major challenge to global sustainability
- The unique attributes of electricity make it indispensable for satisfying energy needs

Conclusions and Recommendations

- There is a strong belief that global sustainability is plausible and achievable, but not inevitable, nor easily attained.
- The world is simultaneously optimistic and pessimistic about the possibility. On the negative side, world population continues to rise and concentrate in "megacities" where pollution grows worse. Many people live in abject poverty and lack access to the resources, infrastructure, and education needed to advance.
- On the positive side, the recent record in the U.S., Europe, and Japan gives hope that technology-driven development brings with it mediating forces and favorable trends that can be applied in the developing world.
- Work by Ausubel and others suggests that increasing productivity and reducing emissions at a rate of around 2%/year would be sufficient to achieve sustainability. This "2% Solution" is in line with historic trends on many fronts, from energy to agriculture, and will require continuous technological innovation and steady technological diffusion around the world over the next century. R&D must be robust to carry this off.
- Given the availability and proximity of coal to the most rapidly growing regions of the world, the highest R&D priority should be given to the most efficient and environmentally benign processes for coal-fired generation.

- Second highest priority for power production should be given to distributed generation and storage technologies that might (1) alleviate the urban concentration of economic development and stem the migration to the mega-cities, and (2) create an alternative to the cost and complexity of traditional infrastructure development.
- High R&D priority should also be given to both the science and technology needed to address the climate change issue. Science must address the issue on a global scale, and technology must focus on accelerating the development of non-fossil energy sources.
- Information technology R&D should be pursued as a means of accelerating the diffusion of technology to developing nations.
- Materials science should also be pursued with the intent of accelerating the dematerialization trend, and creating future approaches to urban and industrial ecology.

Appendix D

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