EPRI

Electricity Technology Roadmap

MEETING THE CRITICAL CHALLENGES OF THE 21ST CENTURY

2003 SUMMARY AND SYNTHESIS

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EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • P.O. Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

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Contents

Foreword

The Electricity Technology Roadmap represents a collective vision of the opportunities for electricity to serve society in the 21st century through advances in science and technology. It remains a living document, owned by all stakeholders in the electricity enterprise, and is intended to be periodically updated.

The Electricity Technology Roadmap initiative began in 1997. Although spearheaded by EPRI, over 200 organizations—including energy companies, equipment manufacturers, government agencies and research laboratories, universities, foundations, engineering and consulting firms, trade associations, financiers, environmental groups, and others—contributed to the framing of this vision and the development of an initial report in 1999. It was organized around five Destinations that are critical milestones on the path toward achieving a sustainable global energy economy by 2050. These Destinations are: (1) Strengthening the Power Delivery Infrastructure, (2) Enabling the Digital Society, (3) Boosting Economic Productivity and Prosperity, (4) Resolving the Energy/Environment Conflict, and (5) Managing the Global Sustainability Challenge.

This 2003 Roadmap edition begins the more detailed planning needed to "build the road" to reach these five Destinations. A formal effort to expand and extend the Roadmap began in early 2002 by identifying the most fundamental challenges to be met through research and development. Teams worked on 14 broad "Limiting Challenges" that require technical breakthroughs to meet society's requirements for electricity and electricity-based services in the new century. This work included laying out specific R&D programs to address the "critical capability gaps" in knowledge and technology for each of the Limiting Challenges.

This report is a summary and synthesis of the research described by the various Roadmap teams. It draws out the major conclusions and puts forward a set of priorities and recommendations for accelerating electricity-based R&D in the U.S. and around the world. This report represents the top tier of a set of more technically detailed reports available online at epri.com. It also links to a number of EPRI overview reports of strategic significance, such as the 2003 report titled Electricity Sector Framework for the Future, which is also available on epri.com. Further details on the Roadmap's background and development process are described in Appendix B.

CHAPTER 1

Roadmap Introduction and Executive Summary

The world of the early 21st century faces unprecedented challenges in caring for its peoples, resources, and environment. Electricity transformed the past century, and it will be even more crucial in years to come.

But the electricity infrastructure itself must first be transformed. The U.S. electricity enterprise is far from ready for the demands of the coming digital economy, an ever more competitive world, and its endangered environment.

The opportunities for society are boundless if we act now with vision to end decades of under-investment, marshal our resources, and focus on the critical innovations needed.

This Electricity Technology Roadmap offers such a vision and a path to realizing electricity's promise for the entire world.

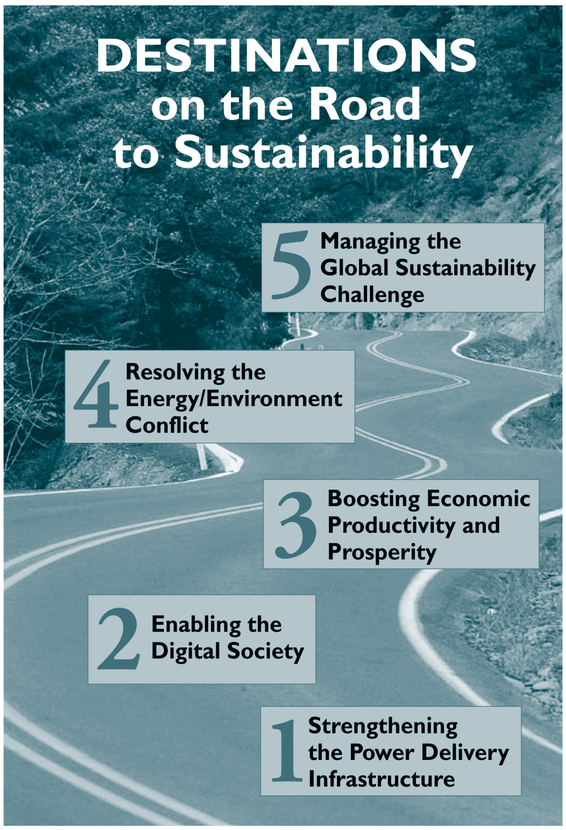
Electricity is far more than just another form of energy. Over the past century, it has been the wellspring for technical innovation and a prime mover for the creation of new industries, jobs, and services. Since Edison's day, its influence has been so important that the U.S. National Academy of Engineering ranked electrification as the greatest engineering achievement of the 20th century, ahead of automobiles, telecommunications, computers, and even healthcare in terms of its positive impact on quality of life.

Electricity's global impact can be—and, we believe, must be—even greater in the 21st century, but only if critical development and investment decisions are made now to transform the electricity system for the pressing needs of the new century. There are three overriding imperatives:

- Meet the precision-power requirements of the emerging digital economy
- Create the clean-energy portfolio required for long-term environmental sustainability
- Accelerate access to the benefits of electricity among all the people of the world

Today's choices have enormous implications. With enhanced investment in electricity innovation, opportunity can continue to unfold in the new century. Without such investment, the key role that electricity can play in meeting some of society's most pressing needs—economic prosperity, environmental sustainability, and human development—will be greatly compromised. Which future will we choose?

We face the 21st century's burgeoning needs for energy largely with the capabilities of the past. The decades before us will place radically different and more challenging demands on the electricity system than can be met with current technology and infrastructure investment rates. But we lack a clear vision of the new opportunities open to us and the dangers of inaction. What we do in the next decade to increase the functionality, value, and availability of electricity worldwide will make a dramatic difference in our shared future.



Source: EPRI

FIGURE 1-1. The five Roadmap Destinations underscore the critical role of electricity in achieving global sustainability.

The Electricity Technology Roadmap ("the Roadmap") provides a global vision for realizing electricity's essential value to 21st century society, a plan to set strategic technological priorities, and an outline of the associated research, development, and delivery requirements needed to achieve this vision. The Roadmap's goal is to encourage the debate, consensus, leadership, innovation, and investment that will enable electricity to realize its potential for increasing quality of life on a global scale. This chapter introduces the Roadmap and provides an overview of its contents.

The Roadmap Vision and Destinations

Given the central importance of electricity to enhancing quality of life, EPRI launched the Electricity Technology Roadmap initiative with the fundamental societal concerns of the 21st century in mind. The initial version of the Roadmap, published in 1999, defined a vision based on five essential Destinations:

1. **Strengthening the power delivery infrastructure**
2. **Enabling the digital society**
3. **Boosting economic productivity and prosperity**
4. **Resolving the energy/environment conflict**
5. **Managing the global sustainability challenge**

The Roadmap Destinations flow from a set of logical propositions that begins with the current state of the domestic power infrastructure and continues through to the benefits of global electrification. The argument is summarized as follows:

Modernization of the electricity infrastructure can improve power system reliability and security, while reducing the cost of power disturbances and outages. The current electricity infrastructure was not designed to meet the pace and rigor of competitive electricity markets, or the new demands of the digital age. Modernization can cut the cost of power reliability fluctuations dramatically—up to 80%—while improving the functionality and security of the nation's most vital infrastructure.

Dramatic power system improvements will require new and improved technology. The key to future economic growth and better security is to make the power system smarter, not just bigger. An intelligent, adaptive power system can provide the reliable, high-quality power needed to run a 21st century economy. The Roadmap calls for the creation of a smart power system over the next 20 years by augmenting the current network with advanced sensors and communications, coupled with automated, adaptive power electronics control technology. The economic payback would be rapid.

The modernized electricity system will facilitate the digital age. Advanced technology could functionally integrate electricity and communications into an "energy web" capable of both supporting a new wave of interactive energy/information services for consumers and supplying digital-quality power for business and industry.

The modernized electricity system will enable productivity improvement and GDP growth. The Roadmap estimates that modernizing the electricity infrastructure could increase economic productivity by 0.7% per year over business-as-usual conditions. In the United States alone, this translates into about $3 trillion per year in additional GDP by 2025.

Modernizing the electricity infrastructure could translate into $3 trillion per year in additional GDP by 2025 in the U.S. alone.

Modernization will also lead to more efficient use of electricity. The energy web will facilitate the use of real-time price signals, enabling greater consumer control, and accelerate the use of energy-efficient appliances and processes.

The societal benefits will far outweigh the costs. Development and full deployment of a modern, smart electricity system would cost an average U.S. household less than $5 per month. This cost could be more than offset by end-use efficiency improvements. In addition, the advanced system would stem power disturbances that now cost each household several hundred dollars per year in the form of higher prices for goods and services, while enabling greater personal income through enhanced economic productivity. In addition, society would benefit from a cleaner environment and greater infrastructure security. Moreover, because electricity can carry information as well as power, modernizing the system to couple energy and information is the only practical means to ensure that energy use becomes continuously smarter and more efficient.

Universal access to electricity will have far-reaching benefits for the developing world. Economically, this will lift all boats. Nearly two billion people in the developing world have little or no access to electricity. The ultimate Roadmap goal is to achieve universal, global electrification by 2050, ensuring that everyone has access to at least 1,000 kWh per year. The economic benefits would be worth tens of trillions of dollars in additional GDP for the poorest nations while creating significant new markets for goods and services.

Universal electrification will require roughly 10,000 GW of global generating capacity, or three times the current level, as well as an advanced portfolio of clean, affordable generation technology options.

Roadmap Priorities in a Nutshell

As part of an analysis of the five Destinations, Roadmap participants identified three high-priority innovation goals that are most essential to assuring global economic and environmental health. They are:

- **Smart power**—The design, development, and deployment of the smart power system of the future
- **Clean energy**—The accelerated development of a portfolio of clean energy technologies to reduce air pollution and address climate change
- **Power for all**—The development of policies and tools to ensure universal global electrification by 2050

Smart Power

A truly "smart" power delivery system will include automated capabilities to anticipate problems, find solutions, and optimize performance. Such a system will deliver the high-quality power needed by sensitive digital technologies. Over time, it will also evolve to support dynamic two-way communication with advanced end-use devices. The basic building blocks include advanced sensors for wide-area system monitoring and control, faster-than-real-time data processing and pattern recognition software, solid-state power flow controllers, and two-way energy/information consumer access portals. Conceptual and architectural design of this smart power system has begun, and component development and demonstration is proceeding, albeit slowly.

Clean Energy Technology to Mitigate Climate Change

Growing concerns about greenhouse gas emissions (see Chapter 3) foster a multidisciplinary approach to CO_2 management that includes cleaner, cheaper, and more efficient power generation and end-use technologies, as well as commercially viable carbon sequestration solutions. Over the medium term, perhaps the greatest gains could come from increasing the portion of world energy that comes from low- or no-emission power sources. However, this could not be accomplished without a massive investment of labor and funds, and the close collaboration of policymakers around the world. For example, stabilizing atmospheric concentrations of CO_2 at 550 ppm (twice the preindustrial concentration level) would require that 75% of electricity be generated from zero-emitting sources by 2100, and that carbon intensity (Carbon/$GDP) be no more than 10% of today's value.

Universal Global Electrification

The Roadmap calls for universal global electrification by 2050, at a minimum level of 1,000 kWh per person per year. This would meet basic needs, improve most measures of quality of life, and enable universal participation in the global economy. About one third of the world's population is at this level today. Given projected population growth, universal electrification will require bringing electricity to 100 million new users every year for the next 50 years. Anything less will threaten global security, economic growth, social progress, and the preservation of critical environmental resources. Electricity is the solution, the essential foundation for a sustainable world.

The payoff from implementing the Roadmap recommendations is clearly immense in economic, societal, and environmental terms. Some elements of this payoff are further described in the Roadmap case studies discussed later in this chapter.

Roadmap Recommendations

The recommendations in this edition of the Roadmap are based on increasing the potential for electricity-based innovation to contribute meaningful solutions to societal challenges. These solutions include improving infrastructure reliability and security, stimulating economic growth, reducing the environmental impact of energy use, and extending human access to the benefits of electricity. The specific recommendations are to:

1. **Increase U.S. energy R&D funding** to the $10 billion per year level. Although this is more than double the current level of energy R&D funding, it represents only about 3% of total U.S. R&D expenditures, about 0.1% of the U.S. annual GDP, and less than 5% of annual electric utility revenues.
2. **Increase public/private collaboration** at both the national and international levels in energy R&D, particularly in areas related to the smart power system, climate change, and global electrification. This collaboration will increase the efficiency and potential for success of the limited R&D resources currently available for energy.
3. **Expand the outreach activities** of the Electricity Technology Roadmap to establish cooperative linkage with other research initiatives and energy technology roadmaps around the world and substantially increase global participation in the next Roadmap update.
4. **Continue to update the Roadmap** at appropriate intervals to incorporate new points of view from around the world, new technological breakthroughs and insights, and new trends in global electrification. Future updates will better integrate public and private sector planning and investment strategies.
5. **Focus the R&D effort** on the "Limiting Challenges" identified in the Roadmap:

   Near-term priority activities (2004–2010)

   - Design, develop, and begin deployment of the smart power system, including electronic control of the delivery infrastructure, and the "energy/information portal" to replace the traditional meter
   - Accelerate R&D efforts on nuclear power, clean coal, renewables, and end-use energy efficiency
   - Develop analytical models to simulate technological and economic factors involved in hydrogen production, storage, transportation, and end-use technologies

   Mid-term priority activities (2010–2025)

   - Deploy the efficient, smart power supply system throughout the developed world
   - Open a new era of consumer-driven electricity/information services

- Pilot test and demonstrate advanced coal-based generation and carbon capture/ sequestration technologies
- Expand deployment of advanced nuclear and renewable generation as key elements of carbon management for the future
- Demonstrate practical hydrogen production and usage for both mobile and stationary applications
- Develop lower-cost and more reliable electricity generators and microgrids for rural electrification in developing countries

Long-term priority activities (2025–2050)

- Support the emergence of competitive markets for the electrification of developing countries
- Achieve universal access to the benefits of electricity
- Develop the technical means to transition away from fossil fuels in both the developed and developing worlds
- Deploy advanced generation systems optimized for both electricity and hydrogen production
- Construct an electricity/hydrogen production and delivery infrastructure for both vehicular and stationary applications

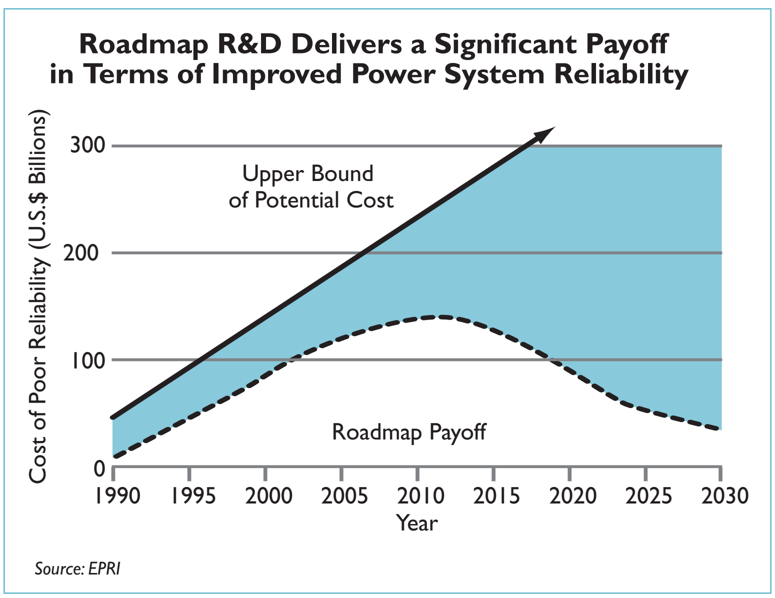


FIGURE 1-2. The deployment of Roadmap technologies could dramatically improve power system reliability.

The Roadmap Payoff—Case Studies

Improving Power System Reliability. The Roadmap's research found that the current costs of poor reliability to the U.S. economy have grown to at least $100 billion per year —and that's in a normal year, not including extreme events such as the 2003 Northeast Blackout. The magnitude of poor reliability, caused by fleeting and complex disturbances that are parasitic in nature, goes largely unreported by millions of businesses. As a result, it's difficult to precisely determine the corresponding economic burden. Power disturbance costs are passed on to all types of consumers in the cost of goods and services, but are most serious in the commercial and industrial sectors. (See Chapter 4 for a detailed description of this issue.)

Technologies identified in this Roadmap, which either are available now or could be available in a few years with accelerated technology development, could conservatively reduce reliability losses by 80% or more, depending on their rate of market penetration. If new technologies for the power infrastructure are not developed and deployed and old systems are allowed to run far beyond their design lives, these losses could be as high as those suggested by the Upper Bound of Potential Cost (as shown in Figure 1-2). Under the Roadmap scenario, however, power quality and reliability-related losses would peak in about 2010 and then begin a steady long-term decline. The technology solutions outlined in the Roadmap focus on (a) real-time monitoring and control of power system conditions; (b) increasing the adaptive "intelligence," automation, and carrying capacity of the power delivery system; and (c) improving the reliability and quality of power at the point of use. (Chapter 3 contains more information on these technologies.)

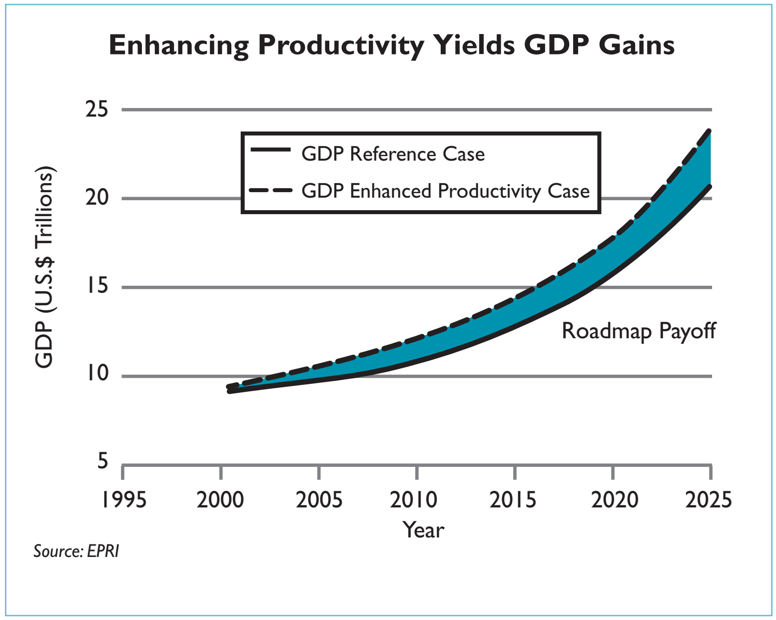


FIGURE 1-3. The deployment of Roadmap technologies could improve GDP by improving productivity growth.

The payoff will be achieved by a combination of remedying deficiencies in the current power delivery system, expanding the system to provide for future load growth, and adding the capabilities needed for a more functional power system. Preliminary estimates of costs and benefits from this three-fold approach to improving the power delivery system are still being developed. An initial study performed by EPRI suggests that research, development, and deployment costs for the transformed transmission system will approach $200 billion over a 20-year period. Costs for the distribution system will be larger, approximately $500 billion over the same period (see Appendix D). This calls for a combined investment level of about $35 billion per year, roughly twice that of today's level of transmission and distribution infrastructure investment.

Increasing Worker Productivity. An enhanced electricity infrastructure, coupled with electricity-driven end-use technologies, has the potential for improving process efficiency and increasing worker productivity. Although electricity is not the only factor contributing to greater productivity, an improved electricity infrastructure with greater functionality and higher reliability and power quality could play an indispensable enabling role, while reducing labor requirements on the shop floor and in the back offices of the 21st century. Moreover, an enhanced electricity infrastructure could place a premium on a skilled workforce able to operate and maintain the digitally controlled equipment of the 21st century. Further, both improved electricity infrastructure and end-use technologies would reduce energy requirements in the process and manufacturing industries, while reducing toxic by-products and emissions.

Under business-as-usual conditions, the existing infrastructure would almost certainly limit the productivity growth potential of the digital economy with its rapidly growing requirements for premium power. Today's large and pervasive economic losses from power disturbances

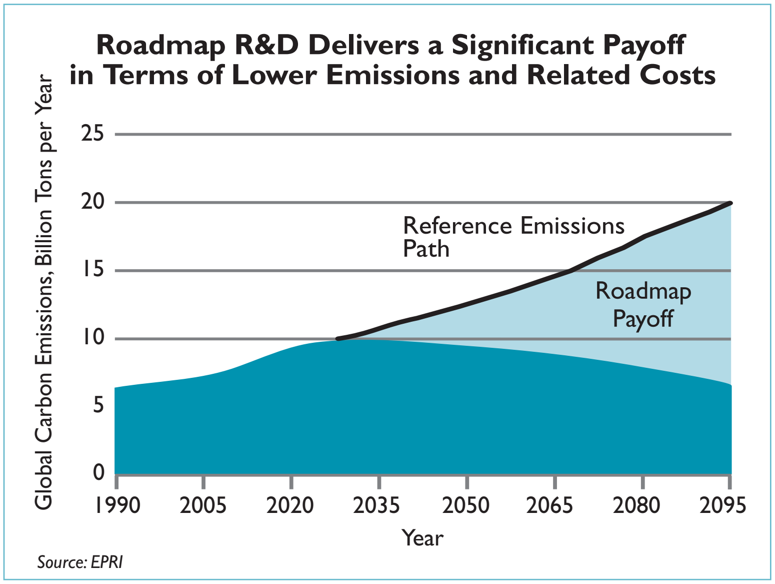


FIGURE 1-4. The deployment of Roadmap technologies could reduce carbon emissions, thereby helping to slow down climate change and its economic and environmental consequences.

are just one indicator of this constraint. An enhanced power system, on the other hand, will stimulate faster and more widespread use of productivity-enhancing digital technology. The Roadmap's goal is a 25% improvement in productivity over business-as-usual growth projections by 2025. As Figure 1-3 indicates, improving productivity growth from 2.5% per year to 3.2% could raise U.S. gross domestic product (GDP) from approximately $21 trillion to $24 trillion by 2025.

Carbon Emissions. The Roadmap also addresses the costs and value of varying approaches to resolving environmental issues. Figure 1-4 shows the gap between the Intergovernmental Panel on Climate Change scenario (Reference Emissions Path) for CO_2 emissions and the much lower CO_2 emissions needed to stabilize atmospheric concentrations at 550 ppm, which is about twice the level in the preindustrial atmosphere. The difference between these two scenarios represents an opportunity to develop and deploy advanced energy technologies that can achieve these objectives, while reducing the cost of emissions reduction by several trillion dollars over the next 50–100 years.

Potential scenarios for filling this gap are numerous, but all essentially depend upon the delivery of progressively cleaner energy through the medium of electricity and/or the use of increasingly intelligent end-use technologies to reduce energy consumption. Coal and gas (coupled with carbon sequestration), nuclear, and renewable power will continue to be the principal energy sources for the next 50 years. Scenarios incorporating a mix of these generation technologies would lead to substantial progress in reducing carbon emissions over the course of the 21st century. (See Chapter 3 for a detailed discussion of power generation options and new opportunities for energy efficiency.)

The Roadmap also envisions hydrogen as a parallel carrier of clean energy, one that could work well in concert with the electricity network to provide additional energy flexibility, storage capacity, and transportability. This would enable society to expand its pursuit of environmental goals in the power and transportation sectors. In principle, hydrogen and electricity (which are energy carriers rather than energy sources) become interchangeable through, for example, the use of fuel cells. However, many technical and economic issues stand in the way of broad implementation of a hydrogen-based energy system. Some of the issues and opportunities of the "electricity/hydrogen economy" are discussed in Chapter 3.

Electrifying the World. As a practical matter, electricity must provide the backbone for the transition to a globally sustainable energy system capable of supporting modern economies. Electricity is an essential precursor for economic progress and well-being, and is the unique energy form that enables technical innovation and productivity growth. However, the important achievements of electrification remain elusive in the less developed regions of the world because populations are growing faster than the current rate of electrification can accommodate.

The Roadmap establishes 1,000 kWh per person per year as a benchmark for electric service. This benchmark reflects basic personal needs for lighting, communication, entertainment, water, and refrigeration, as well as the electricity embedded in the local production of agriculture and other goods and services. There are currently only about 2 billion people in the world above this basic threshold.

Most importantly, electricity brings literacy and access to the modern economic system, helping to create the 500 million new jobs needed each year just to employ the world's growing working-age population. The payoff of bringing everyone in the world to at least this threshold of 1,000 kWh per year by 2050, as shown in Figure 1-6, is to fundamentally improve quality of life for more than half the world's population. The benefits to the global economy by 2050 can be as much as $11 trillion per year in additional economic output from the developing world alone. This is approximately 70% higher than current projections. Global electrification is discussed in more detail in Chapter 5.

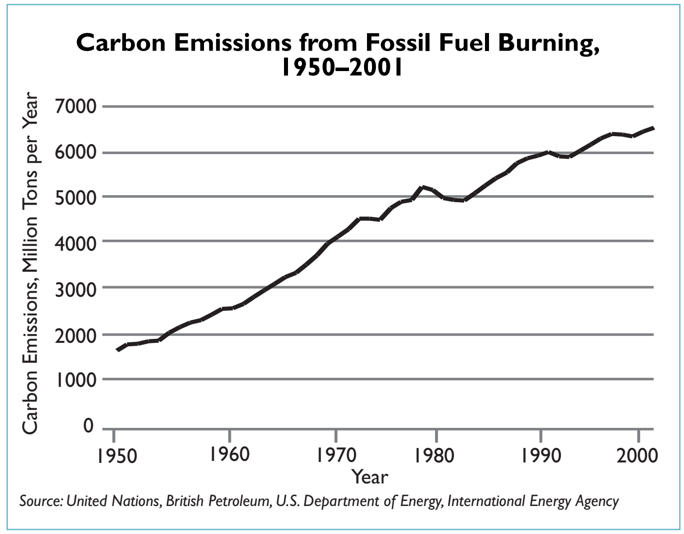


FIGURE 1-5.
Cleaner and more efficient power plants could help reduce the growth of CO_2 emissions related to the combustion of fossil fuels.

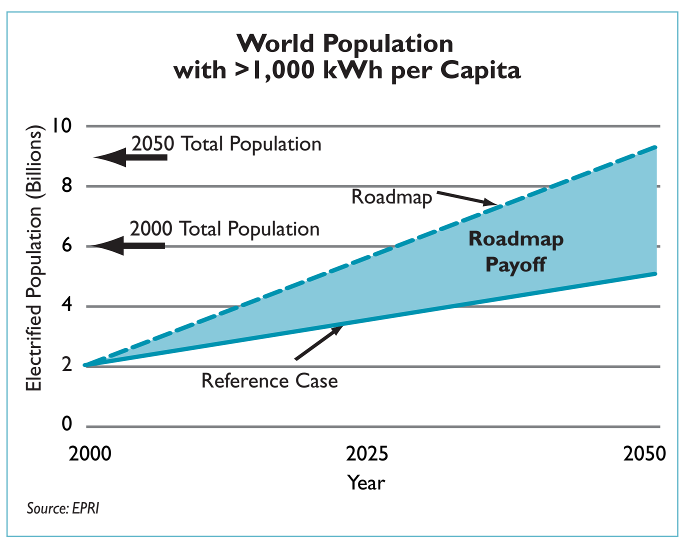


FIGURE 1-6.
The development and deployment of Roadmap technologies could bring basic electricity services to billions more people than the Reference Case.

Limiting Challenges

Realizing the payoff of the Roadmap's technology development agenda is contingent on resolving a series of "Limiting Challenges" that emerged from topical studies conducted in 2002 by a combination of EPRI senior technical staff, experts from industry, academia, and research organizations, and other specialists. The topics covered in the Limiting Challenges studies were selected through staff proposals, industry symposia, and outreach to other stakeholders. Many other topics were considered, but these final 14 were ultimately judged to be the most critical, based on their difficulty and strategic importance. Chapter 6 contains summary descriptions of the Limiting Challenges.

Roadmap research teams were formed to develop R&D agendas for each of the 14 Limiting Challenges. In total, these teams identified more than 100 "critical capability gaps" (CCGs) at a level specific enough to formulate actionable R&D programs. The CCGs represent the issues judged to be most intractable or underfunded in present and planned R&D worldwide, and so were the key issues for the topical studies. Preliminary cost estimates and schedules were developed for each of the CCGs.

Clearly, not all of the CCGs have the same priority and urgency. Further stakeholder input helped EPRI identify the three highest priority R&D tasks for each Limiting Challenge. This final triage yielded a field of 42 highest priority CCGs, shown in Table 1-1, along with the 14 Limiting Challenges. Table 1-2 summarizes the approximate R&D funding requirements for each Limiting Challenge. Chapter 6 provides more detailed descriptions of the CCGs associated with each of the 14 Limiting Challenges.

Table 1-1. Limiting Challenges and Critical Capability Gaps

LIMITING CHALLENGES	Three Highest Priority Critical Capability Gaps		
1. Transmission capacity, control, and stability	• System expansion planning tools to serve the needs of a service-oriented power delivery system	• Transmission and distribution grid automation	• Integration of DER into T&D operations and control
2. Infrastructure to power a digital society	• Self-healing and intelligent electrical network	• DER interconnection standards	• Design and demonstration of AC and DC microgrids
3. Robustness and security of electricity infrastructure	• Probabilistic vulnerability assessment capability	• Fuel-to-end-use modeling of the energy system	• Robust emergency control and automated grid restoration
4. Value of energy storage technologies	• Cost-benefit of storage in a semi-regulated industry	• More cost-effective, high-capacity storage options	• Demos to validate cost and performance
5. Transforming electricity markets	• Demand response, enabled by customer "portal"	• New financial risk models	• Incorporation of infrastructure into market planning
6. Electricity-based transportation systems	• Cost-effective hybrid fuel cell vehicles	• Longer-life batteries and fuel cells for automotive use	• Mobile distributed generation of power
7. High-efficiency end uses of electricity	• High-efficiency electrotechnologies in process industries	• High-efficiency lighting systems	• High-efficiency motors, drives, and power supplies
8. Advances in enabling technologies	• Smart materials, nano-structures and fullerenes	• Technologies that mimic biological processes	• Enhancements in man-machine interfaces
9. Strengthened portfolio of generation options	• Near zero-emission fossil fuel generation technologies	• Technologies for advanced nuclear reactors	• Application of hydrogen as an energy carrier
10. Universal global electrification	• Technology background to reduce financial risks of electrification projects	• Low-cost generation technologies for the developing world	• Better understanding the role of electrification in economic growth
11. Carbon capture and storage technologies	• Breakthrough technologies for economical carbon capture	• Pilot- and full-scale demos of direct sequestration	• Assessment of environmental, legal, and societal issues of sequestration
12. Ecological asset management	• Tools for monetizing ecosystem assets	• Public support for market-based ecosystem management	• Development of markets for eco-asset commodities
13. Improving water availability and quality	• Water management priorities	• Robust water allocation models	• Microscale water management technologies
14. Environmental science	• Understanding health risks of air emissions and toxic compounds	• Understanding climate change impacts and strategies	• Resolution of remaining health concerns related to EMF

Table 1-2. Research, Development, and Demonstration Funding Needed to Address Limiting Challenges

LC Number	Title	Current Funding[1] (U.S. $ Million/Year)	Roadmap Funding Recommendations[1] (U.S. $ Million/Year)
1	Transmission capacity, control, and stability	$200	$1,000
2	Infrastructure to power a digital society	$800	$2,500
3	Robustness and security of electricity infrastructure	$10	$300
4	Value of energy storage technologies	$50	$100
5	Transforming electricity markets	$100	$150
6	Electricity-based transportation systems	$100	$200
7	High-efficiency end uses of electricity	$400	$600
8	Advances in enabling technologies	$500	$1,000
9	Strengthened portfolio of generation options	$700	$2,300
10	Universal global electrification	NA	$400
11	Carbon capture and storage technologies	$200	$300
12	Ecological asset management	$10	$50
13	Improving water availability and quality	$50	$100
14	Environmental science	$700	$900
	TOTAL	**$3,820**	**$9,900**

[1]Includes public and private funding

Financial Requirements and Action Priorities

Meeting the priority activities identified in the Roadmap will require a concerted approach to develop incentives and mechanisms for collaborative public/private funding and management of energy R&D. This will include international collaboration in technologies suitable for the developing world. The Roadmap agenda also includes the establishment of the smart grid and clean energy development as national priorities, worthy of federal, state, and private sector funding. Finally, the Roadmap seeks to urgently provide the means to move the U.S. electricity sector toward the vision of the "21st Century Transformation" articulated in EPRI's Electricity Sector Framework for the Future.

EPRI staff worked with a diverse set of electricity enterprise stakeholders (utilities, trade associations, government organizations, regulators, universities, environmental and consumer groups, etc.) to estimate the R&D funding needed to close all of the CCGs in time to achieve the five Destinations. Based on their analysis, the cumulative U.S. public and private funding requirements to achieve this broad program should increase to $10 billion per year for at least the next decade.

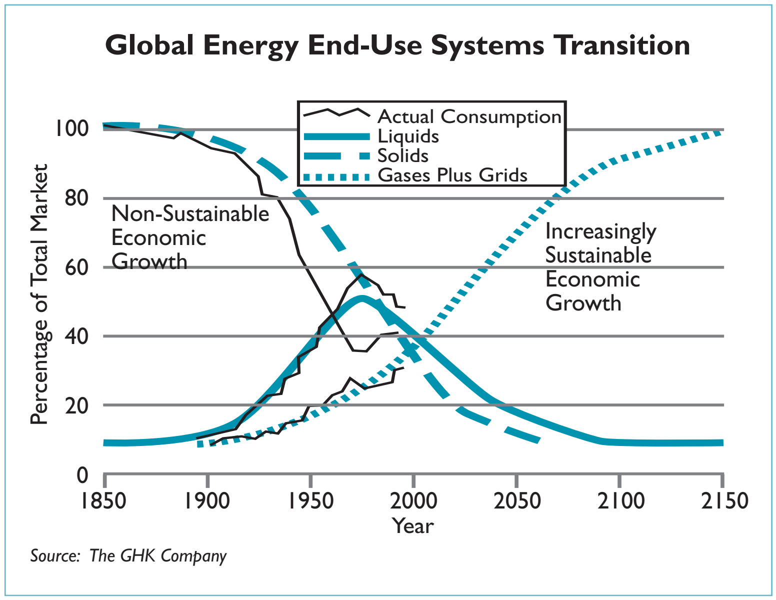


FIGURE 1-7. A fully funded R&D initiative covering short-, medium-, and long-term contingencies is critical to ensuring the transition to more sustainable energy production.

The benefits of the program accrue from stemming losses caused by power disturbances via the smart power system, increasing worker productivity, opening export markets for low-cost clean energy technology, and fostering economic growth through global electrification.

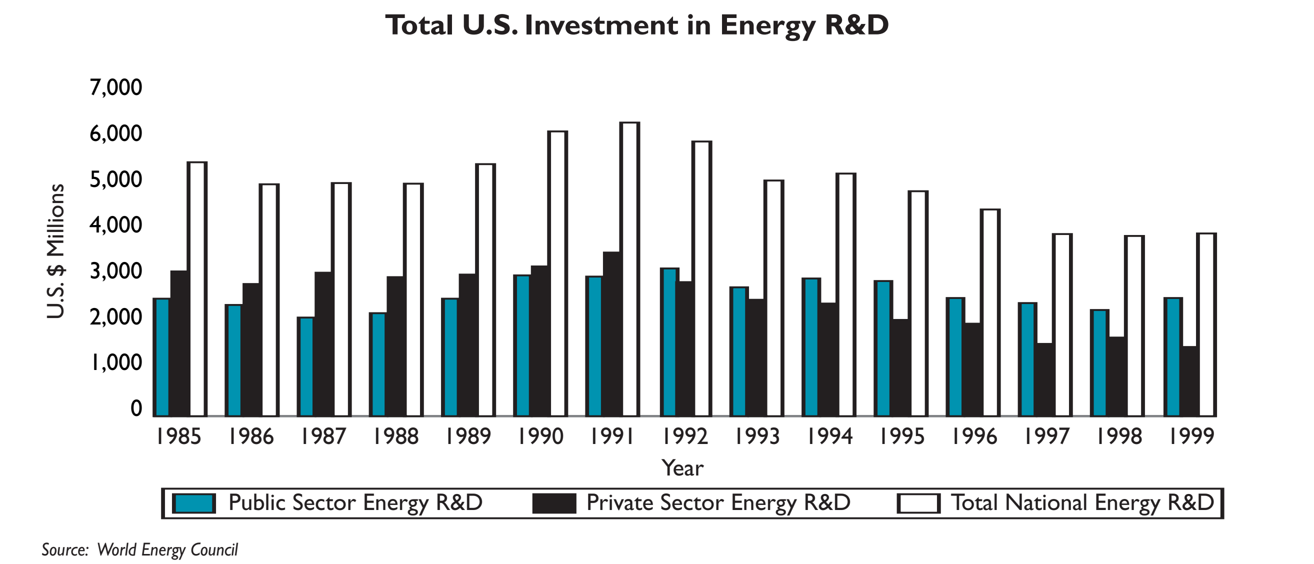


FIGURE 1-8. U.S. investment in energy R&D declined throughout the 1990s.

Role of Public/Private Collaboration in Technology Development

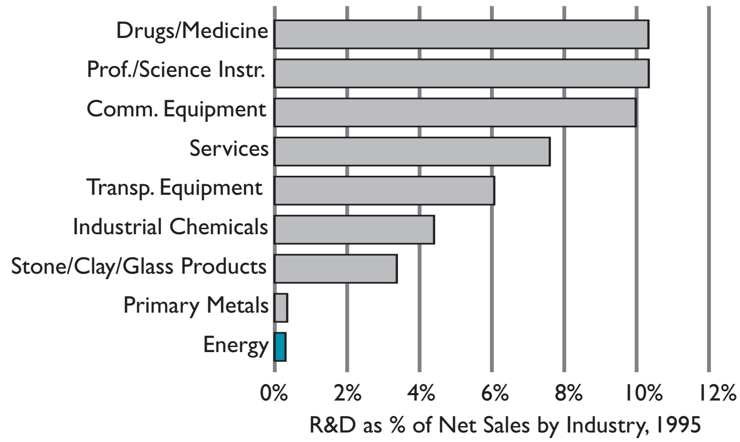
Critical to the success of the Roadmap will be increased public and private sector research funding for critical R&D. Currently, private sector energy R&D investment is less than 0.5% of energy sector revenues, and U.S. federal R&D support for energy is only about 4% of total federal R&D outlays. More disturbing is the downward trend in funding. As shown in Figure 1-8, private sector energy R&D funding declined by about one half over the 1990s, while public sector funding declined by about one third.

This downward trend appears to reflect a desire to become more "competitive," a factor that frequently means reducing short-term costs in areas presumed to be discretionary. Reducing R&D expenditures can have an immediate positive cost effect. The increased potential for poor longer-term corporate performance is difficult to quantify, and is sometimes viewed as a deferrable risk. But, as long as companies are incented to consider R&D for innovation as a cost rather than as an investment, the predictable result is likely to be a self-fulfilling prophecy of declining corporate value.

Structural differences between infrastructure-based industries and so-called high-tech industries make direct comparisons between research funding for different sectors difficult. Nevertheless, the current low and declining funding levels in the electricity sector are not sustainable, and, if allowed to continue, will prevent the electricity sector from achieving the necessary value to the economy and society identified in this report. The Roadmap addresses this problem by prioritizing research requirements for both short- and longer-term time frames. This process, based on the Limiting Challenges outlined in Table 1-1, establishes the basis for research management on an industry-wide basis.

Key to developing a plan and process (including roles and responsibilities) for the public and private stakeholders to work in partnership on critical energy infrastructure R&D needs is appreciating how closely aligned these stakeholders are today on the goals that must be achieved. Appendix E provides a comparison among the goals of the National Energy Policy, the DOE Strategic Plan, and this Roadmap. The commonality between these three visions of the future, particularly for the next 20–30 years, is striking. Thus we have a basis for the public and private stakeholders to come together to achieve these goals in a partnership that leverages resources in the public interest.

Private Sector R&D Investment



Source: Margolis and Kammen

FIGURE 1-9. Historically, the energy industry has tended to invest a smaller portion of its net sales than other industries.

Working in partnership, the public and private sectors can jointly plan and execute infrastructure R&D. They can identify and avoid gaps and overlaps in R&D. Public/private partnerships are an effective way to achieve "mission focus" in R&D planning and prioritization, and to spur R&D productivity. Public/private partnerships are both "good government" and "good business." In addition to leveraging government and industry R&D spending, they provide the following additional benefits:

- Introducing market relevance into infrastructure R&D planning and decision making
- Maintaining a focus on achieving high-value results
- Accelerating the R&D process and transfer of results to the economy and the marketplace

The bottom line—public/private partnerships deliver much more bang for the infrastructure investment buck.

Finally, information sharing is an essential element of public/private collaborative efforts. The Roadmap participants universally advocated free and open exchange of data and information. While recognizing that some information must remain proprietary and confidential, the participants noted that in many situations, the value gained through mutual sharing of technical information would be much greater than the value of preserving confidential information. The critical factor is building understanding and trust. The Roadmap has proven to be a valuable vehicle for convening stakeholders to address this issue.

Next Steps: A Call to Action

Several organizations, including EPRI, are working to implement some of the key recommendations of the Roadmap, focusing on advanced generation technologies, improved environmental performance, and the development of a smart power delivery system. These initiatives are currently yielding research projects with an aggregate annual value of $4 billion or 40% of the $10 billion per year needed to address the full Roadmap agenda. Increasing funding to the levels needed will require a concerted effort to build support for the highest priority near-term initiatives, while carrying forward a longer-term research program on critical issues. Given the scale of the effort required, and the long-term global benefits, greater international collaboration in energy R&D is essential, and should be encouraged and developed through various international channels.

The enormity of the challenges ahead demands a bold initiative that moves beyond the efforts of several organizations working independently on the problems. The energy leaders of the nation—administration officials, key members of Congress, utility executives, and energy policy experts from business and academia—must come together and agree on a common vision and plan of action.

The Roadmap concludes that a strategic science and technology initiative is urgently needed to address the issues surrounding the implementation of the grid of the future, solutions to climate change concerns (including new generation options), and universal global electrification. The Roadmap initiative is essential to avoid conflicting short-term responses that tend to "lock in" existing technologies, remove the constraints on efficient economic development, and accelerate the technology innovations needed for long-term sustainability. The Roadmap promotes sustained innovation as the key to enhancing economic prosperity, productivity growth, and environmental health.

At the dawn of the 20th century, the German mathematician David Hilbert commented on the importance of defining and pursuing a vision of the future:

Who of us would not be glad to lift the veil behind which the future lies hidden; to cast a glance at the next advances of our science and at the secrets of its development during future centuries?

Let us lift the veil and participate in shaping the future through action now.

Report Organization

The remainder of this report is organized into the following five chapters:

Chapter 2, "Roadmap Destinations," provides the basic framework for understanding the objectives and priorities of the Roadmap. Each of the five Destinations is summarized for the reader, along with some of the key issues that must be addressed. This chapter is intended to set the stage for the more detailed technical discussion in Chapters 3–5.

Chapter 3, "Technology Building Blocks," focuses on the technology that must be developed to reach the Roadmap Destinations in time. This includes the smart power system by 2025, and a portfolio of clean energy options by 2050.

Chapter 4, "Vision 2025—Enhancing the Value of the Power System." This chapter lays out the transformed electricity system required to support the digital, knowledge-based industries of the world of 2025. Two contrasting scenarios reveal the economic and environmental advantages to society that would result from modernizing the electricity infrastructure.

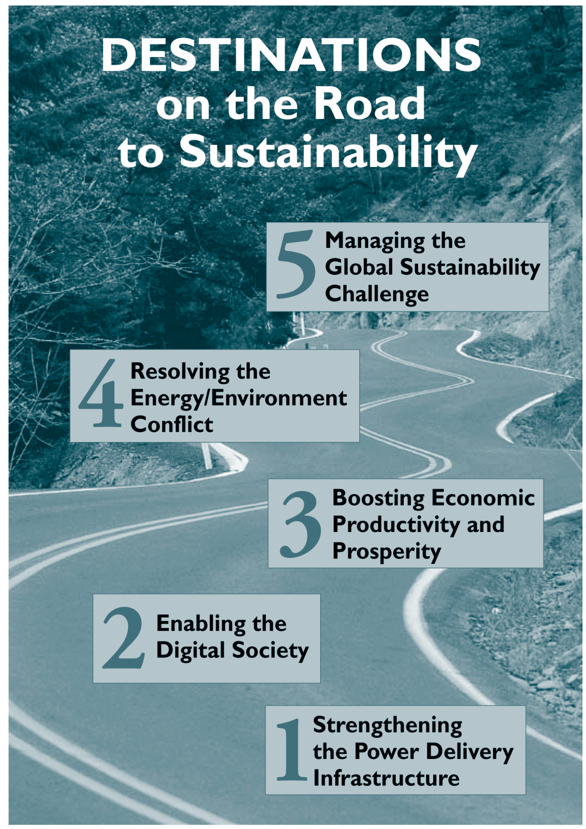
Chapter 5, "Vision 2050—Universal Electrification," examines the ultimate Destination of the Roadmap, that of managing global sustainability. The participants believe that access to abundant and affordable electricity will be at the heart of any and all solutions to global sustainability.

Chapter 6, "Limiting Challenges," summarizes the insights and recommendations of the 14 separate teams focused on the Limiting Challenges. The chapter shows how the Limiting Challenges are now impeding progress toward the Roadmap Destinations. For the convenience of the reader, each of these technical challenges is summarized in a few pages in this chapter, which include diagrams showing how the challenges tie together into the overall plan.

CHAPTER 2 ROADMAP DESTINATIONS

The Roadmap Destinations reflect the most important goals for the electricity and related industries in the next half century. They encompass many untapped opportunities for electricity to power economic and social progress in the United States and throughout the world, and they support a long-term vision that goes well beyond perceiving electricity as just another form of energy. Each of the five Destinations is a critical milestone on the path towards integrating the electricity and information technology infrastructures, thereby creating a new "mega-infrastructure" that will enable the development of numerous innovative products and services. Table 2-1 (see next page) summarizes the five Destinations and how achieving them benefits mankind.

This chapter describes the five Destinations, and highlights some of the key issues. Subsequent chapters deal with efforts to realistically resolve these issues in two time frames—2025 and 2050. Additional information on the Destinations is available in the 1999 Electricity Technology Roadmap and in Appendix B of this report.



Source: EPRI

FIGURE 2-1. The five Roadmap Destinations focus on meeting key societal objectives.

First Destination—Strengthening the Power Delivery Infrastructure

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. The U.S. power delivery infrastructure 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 while relying for the most part upon technologies from the 1950s and 1960s.

Table 2-1. Destinations Summary	
Destination	**Summary**
Strengthening the Power Delivery Infrastructure	An advanced electricity delivery system that provides additional transmission and distribution capacity and "smarter" controls that support dynamic market activity and the rapid recovery from cascading outages, natural disasters, and potential terrorist attacks
Enabling the Digital Society	A next-generation power system that delivers the power quality and reliability necessary for sophisticated digital devices and seamlessly integrates electricity systems with communications systems to produce the "energy web" of the 21st century
Boosting Economic Productivity and Prosperity	New and far-reaching applications of the energy web that increase productivity growth rates across all sectors of the economy
Resolving the Energy/Environment Conflict	Clean, cost-effective power generation technologies combined with workable CO_2 capture, transport, and storage options
Managing the Global Sustainability Challenge	Universal access to affordable electricity combined with environmentally sound power generation, transmission, and delivery options

The North American power grid is divided into four regions for operational purposes—Eastern, Western, Texas, and Quebec. The flow of power within individual regions is growing rapidly as the U.S. power market restructures, with buyers and sellers seeking the best deals across ever-increasing distances.

As shown in Table 2-2, capacity loading on electrical transmission lines is reduced as the distance of the power flow grows. The value of bulk power transactions has increased to the point where more than one half of all domestic generation is now sold on the wholesale market. This growth, however, comes at a time when many parts of the North American transmission system are already operating close to their stability limits. Exacerbating the situation, transmission system expansion is dwarfed by the increase in demand. As a result, grid congestion is growing around the country, as indicated by the near doubling in calls for "transmission loading relief" between 1997 and 2003, as shown in Figure 2-2.

Table 2-2. Capacity Limits for Electrical Transmission Lines

Voltage	Length (Miles)	Maximum Capacity (GW)
765	100	3.8
	400	2.0
500	100	1.3
	400	0.6
230	100	0.2

Source: Edison Electric Institute

Electricity is the last of the major infrastructure industries to fully embrace modern digital control technology, in part because (1) capital investment has slowed dramatically under cost and policy uncertainty, and (2) the technology to cope with high voltage levels is costly. Moreover, competitive wholesale electricity markets have begun to shift power flow patterns in ways the power delivery system was not designed for, and both regulation and market design have been slow to respond to this problem. Most recently, the series of cascading outages in the Northeastern U.S. on August 14, 2003 brought this reality home to nearly 50 million Americans. Similar outages in London, Italy, Denmark, and Sweden testify to the global nature of this problem.

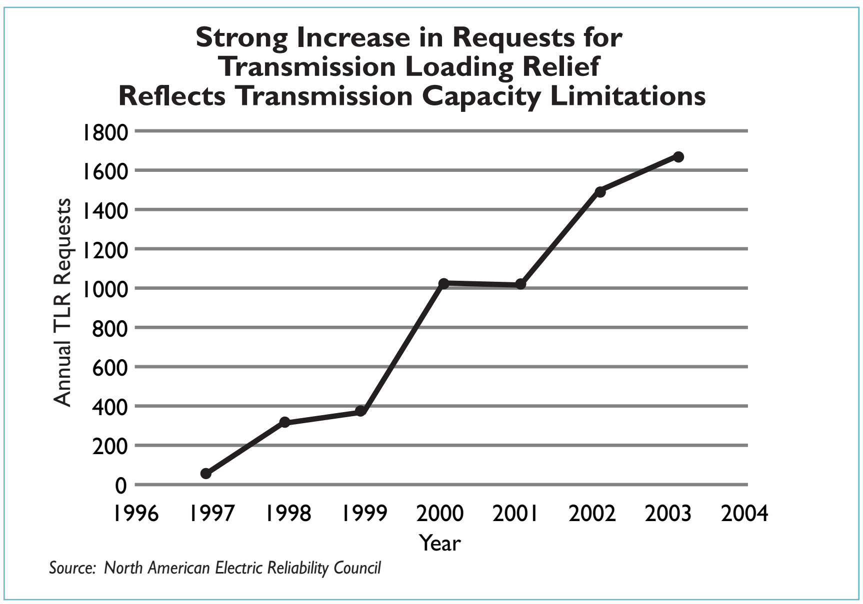


FIGURE 2-2. Today's transmission infrastructure must be overhauled to meet tomorrow's power needs.

Improving the Electricity Infrastructure

Improving the electricity system to prevent large-scale incidents such as the 2003 blackout will require significant investment in new technologies to establish a flexible, reliable, and easily scalable infrastructure. Over the short to medium term, research will focus on:

- Enhancing and commercializing digital controls that can replace aging electromechanical switches
- Integrating distribution automation with office and industrial buildings
- Improving the system's ability to respond to power disturbances (both natural and man-made) through the development of adaptive islanding and similar technologies

Over the longer term, research will support the transformation of today's power generation, transmission, and distribution systems into an integrated network capable of responding in real time to literally billions of transactions. This kind of sophisticated infrastructure will be essential to the flourishing of dynamic markets for electricity and electricity services. For more information about these technologies, see Chapter 3.

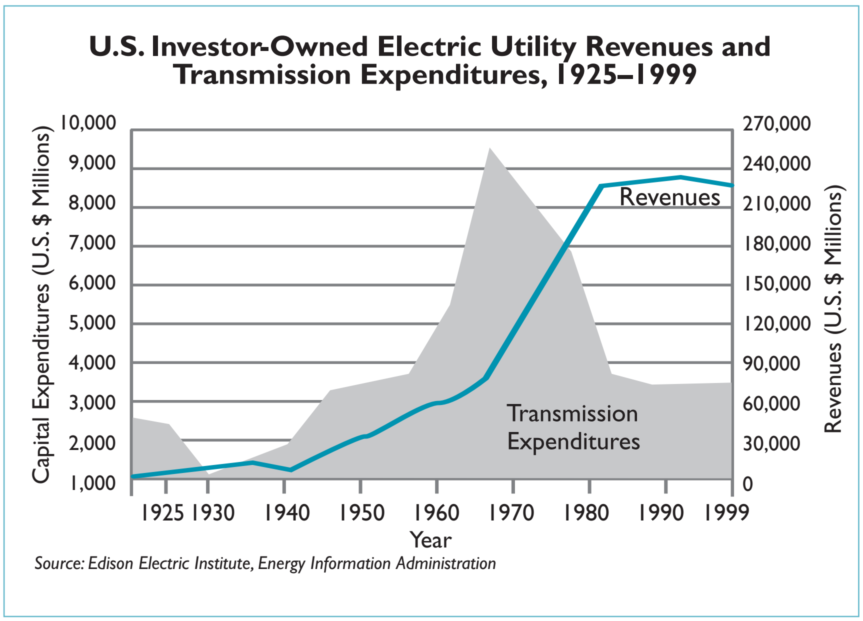


FIGURE 2-3. Despite higher revenues, utilities have been reluctant to invest in transmission infrastructure due to regulatory and market uncertainties.

Second Destination—Enabling the Digital Society

Increasing electricity's value to society will require a fundamental transformation of the electricity system to support new technologies that are pervasive in industrial production and in determining consumer trends and lifestyles. The key will be to use real-time sensors, communications, and controls to convert the current power system into a smart "energy web." As a result, the traditional boundary between electricity provider and user will gradually crumble as the flow of electrons—in the form of communication and energy—takes on the attributes and behaviors of integrated networks.

Developing the Smart Power System of the Future

The power system of the 21st century must be radically transformed to meet the changing needs of diverse stakeholders: that is, industries seeking greater productivity and profitability, governments seeking greater energy security, utilities seeking greater product and service value, and society at large searching for an affordable better life. The productivity and service needs of the 21st century consumer will require an electric power system with greater capabilities than anything that exists today. The drive will be to open the door to an array of entrepreneurial, energy/information services that take advantage of the much greater functionality offered by the energy web.

The productivity and service needs of the 21st century consumer will require an electric power system with greater capabilities than anything that exists today.

The architecture for this new electricity system is emerging through early research on real-time complex network management and enabling platforms. That framework envisions an integrated, self-healing, electronically controlled electricity supply system of extreme resiliency and responsiveness—one that is fully capable of responding in real time to the billions of decisions made by consumers and their increasingly sophisticated microprocessor agents. In short, we must create an electricity supply system that provides the same efficiency, precision, and interconnectivity as the billions—ultimately trillions—of microprocessors that will depend on it.

Technological progress needs to happen on a broad front, but the linchpin is likely to reside in consumer-focused technology that could replace the traditional meter with an "open portal," allowing a two-way flow of real-time information, knowledge, communication, and energy. This would link every microprocessor-controlled electrical device with the open marketplace for goods and services, including power. Technology that can provide an entirely new dimension of choice for consumers could become the catalyst for widespread change, as it has in telecommunications and other industries. All consumers (industrial, commercial, and residential) would become full participants in the marketplace, responding not only to price signals but also to service and product differentiation. The technical underpinnings of the smart power system are described further in Chapter 3.

Third Destination—Boosting Economic Productivity and Prosperity

Economic growth has been highly correlated with electricity use over the past century. The cause and effect relationship is too tightly bound to determine the primary driver, but clearly today neither can proceed without the other. Will this hold true in the future? Through increasingly sophisticated control of electricity, industry and business have a unique ability to focus both energy and information with great precision, yielding higher-value products and services, from computers and instrumentation to database applications. Such uses of electricity will be increasingly dominant in the 21st century, as electrically driven and controlled processes and devices become ever more sophisticated and information-demanding.

For this reason, electricity seems destined to continue its historical trend of claiming an ever-increasing share of total energy use. In the U.S., electricity use grew from 10% of primary energy consumption in 1940, to 25% in 1970, to nearly 40% today. Maintaining this momentum, electricity is expected to account for more than 50% of total U.S. energy consumption by 2050. This percentage may be even greater if transportation moves toward the efficiency and environmental advantages of electric drive. As its share grows, electricity will contribute to an ongoing reduction in total energy use intensity (energy per dollar GDP). Similarly, as the productivity of information services improves, electricity intensity (electricity per dollar GDP) should also continue its long-term decline.

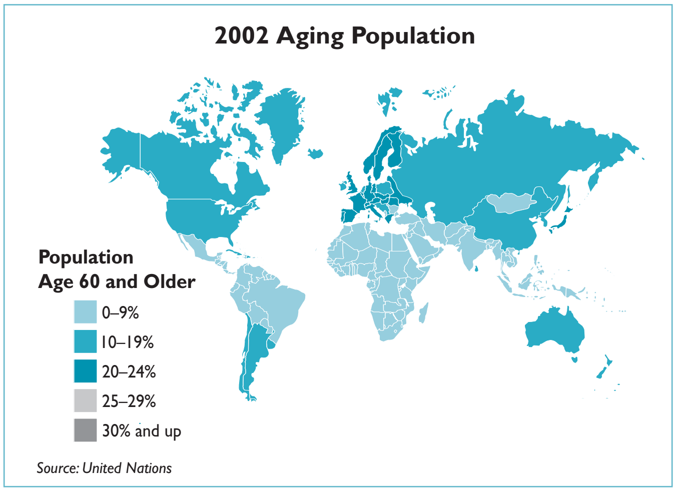


FIGURE 2-4. Today, the workforce is large enough to support the current number of retirees.

Increasing Productivity Growth Rates Above the Baseline

Roadmap participants believe that heightened productivity is possible through the accelerated development and use of innovative science and technology. At a minimum, the energy web should allow productivity gains tied to digital technology to surge ahead unabated by infrastructure deficiencies. At the other extreme, a new technology platform based, for example, on the convergence of IT, biotech, advanced materials, nanotechnology, and the energy web, could emerge in the next decade, leading to a new round of industrial development and another surge in productivity. The Roadmap explores a number of enabling technologies, each with enormous potential for stimulating economic growth over the course of the next few decades.

This sustained long-term growth in labor productivity is imperative. The U.S. is facing uncomfortable choices in supporting aging baby boomers as they enter their retirement years. The alternatives are stark. If the nation fails to double productivity by 2050, it will be forced to either double the tax rate on those left in the workforce, or cut their benefits and make them work significantly longer.

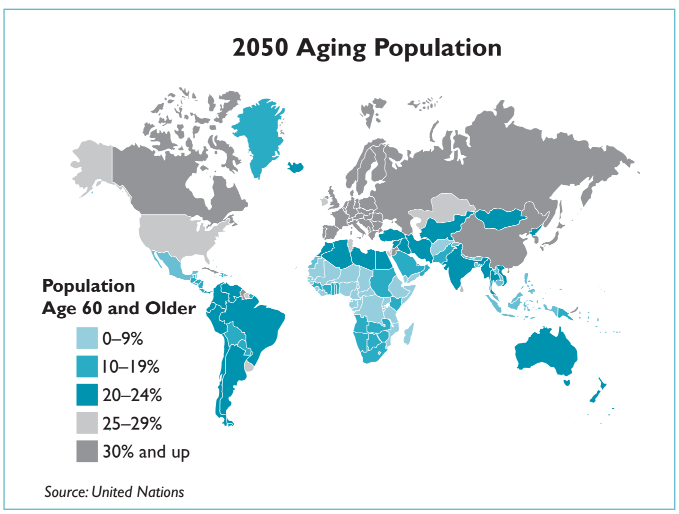


FIGURE 2-5. Tomorrow's workforce, particularly in the developed world, will have to dramatically increase productivity to support an aging population.

As shown in Figures 2-4 and 2-5, productivity is also a global issue, as projections indicate the "graying" of populations worldwide. The phenomenon appears to be especially acute in the developed world. However, if current trends continue, all nations will eventually have to cultivate economies that are so productive they can continue to grow, even as the available labor pool shrinks.

The U.S. needs to again find ways to increase productivity growth rates across the board, as it did in the 1950s and 1960s. Fundamental technology change, built upon the platform of a revitalized electricity sector, is the soundest way of ensuring that the nation has the resources to support an aging population. Failure to do so could result in intergenerational conflict and a declining quality of life for all.

The economic and social payoff from more rapid productivity growth is covered in greater detail in Chapter 4, which examines productivity advantages in the context of 2025. Technologies that may fuel productivity growth are covered in Chapter 3.

Fourth Destination—Resolving the Energy/Environment Conflict

The fourth Roadmap Destination focuses on the substantial challenge facing society as it attempts to resolve the historic conflict between energy use and environmental impact. The issue has taken on global dimensions given the direct ties of energy use to population growth, rising economic aspirations in the developing nations, and growing concerns about greenhouse gas (GHG) emissions-induced climate change.

Without a major change in the structure and composition of global energy and transportation systems, the world will have only limited means for dealing with the growing energy/carbon challenge. According to Roadmap participants, CO_2 and other GHG emissions are 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. In many ways, the challenge of mitigating climate change without adversely impacting human economic opportunities is one of the most important aspects of the climate change debate.

In the context of the energy/carbon challenge, electricity remains the most practical means of using renewable and nuclear energy sources, improving fossil energy efficiency, and accelerating the long-term trend of removing carbon from the global energy system.

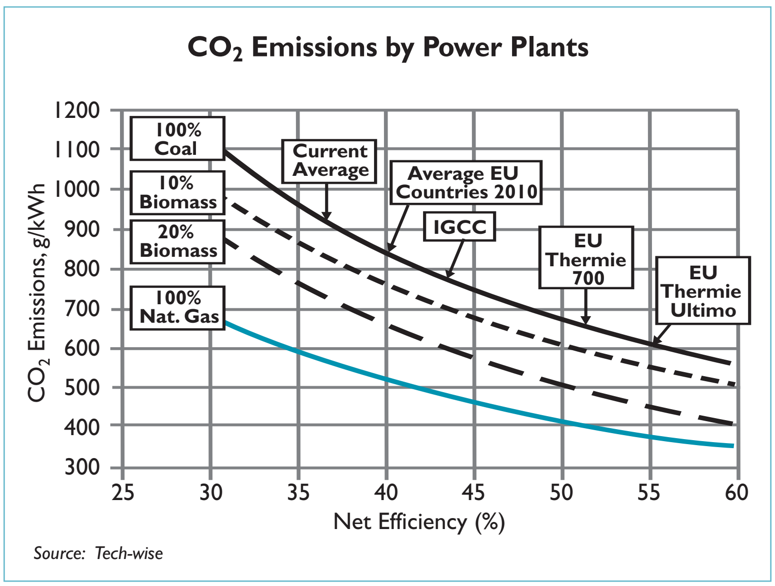


FIGURE 2-6. More efficient fossil steam plants could be one important part of mitigating the environmental impacts of power generation.

Over the short and medium term, improving the emissions and efficiency profile of new coal and natural gas plants is the most practical option for managing atmospheric CO_2. Figure 2-6 shows how (1) substituting natural gas and biomass power for coal power, and (2) improving the efficiency of both coal- and gas-fired plants can reduce CO_2 emissions. It compares hypothetical generation portfolios consisting of 100% coal power, 90% coal and 10% biomass power, 80% coal and 20% biomass power, and 100% natural gas power at various net efficiency levels. Overall, the natural gas portfolio emits less CO_2 than the other four options at all efficiencies. However, replacing relatively small portions of the coal portfolio with biomass (which has a net zero impact on CO_2 emissions) could reduce CO_2 emissions at low cost. Likewise, ultra-efficient coal plants (such as the European Union's Thermie 700 and the Thermie Ultimo projects, which can raise steam temperatures to over 700°C) as well as low-emission integrated gasification combined-cycle plants (IGCC, in which gasification is combined with power generation) could also significantly reduce emissions. Another complementary option for mitigating CO_2 emissions while maintaining coal generation capacity is sequestration technologies that extract CO_2 from the gas stream and store it for decades or even centuries.

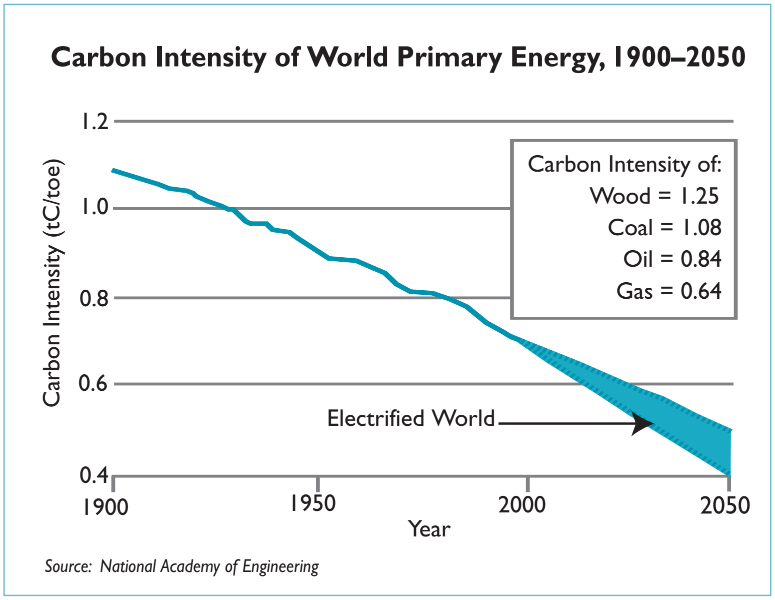


FIGURE 2-7. Greater electrification could accelerate the decline in global carbon intensity.

Over the longer term, renewable energy will play an increasingly important role in expanding distributed resources in low energy-density regions. However, Roadmap participants concluded that nuclear energy is the only non-carbon generating option that can be confidently deployed on a sufficiently large scale to meet the very large gap in 21st century global clean power requirements.

Accelerating the Historic Trend in Carbon Reduction

Considerable progress in the reduction of carbon-intensive fuels has occurred since the mid-1800s, facilitated to an ever-greater degree in the 20th century by electricity. Beginning in the early part of the 19th century, wood yielded in time to coal, and coal, in turn, yielded to oil and natural gas—each with progressively less carbon per unit of energy, as illustrated in Figure 2-7. The role of nuclear and renewable energy is evident in this figure, which shows the future decline in carbon intensity to a level well below that achievable with natural gas, the least carbon-intensive of the fossil fuels. This progress, if maintained through continued technology advancement, puts the world on a predictable trajectory toward a clean, electricity- and hydrogen-based energy economy by about 2050. The Roadmap stakeholders believe the rate of carbon removal per unit of energy can and should be accelerated through faster technology development and implementation. The goal is to stabilize atmospheric concentrations of greenhouse gases, including CO_2, at safe levels.

Figure 2-8 shows that there are multiple pathways to reaching stable atmospheric concentrations of CO_2. For example, maintaining today's concentration of approximately 350 ppm would entail reducing CO_2 emissions to roughly zero by the turn of the next century and maintaining that level indefinitely. Maintaining atmospheric concentration at 550 ppm (a target widely used in analytical treatments of climate change) is consistent with a rise in emissions over the next fifty years, followed by a decline to about 7 gigatons of carbon per year by 2100, and a continued decline thereafter. A strategy of stabilizing concentrations at 750 ppm would allow emission rates to reach nearly 15 gigatons before beginning to decline. Note that in the long term, all stable trajectories decline to substantially less than current emission levels and that decisions about greenhouse gas emissions made over the next few decades will have consequences that will last into the next century and beyond.

Technologies that could help reduce carbon emissions over the short, medium, and long term are discussed as part of the technology outlook for generation in Chapter 3.

Fifth Destination—Managing the Global Sustainability Challenge

Pursuing 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 technology categories include, at a minimum, the following:

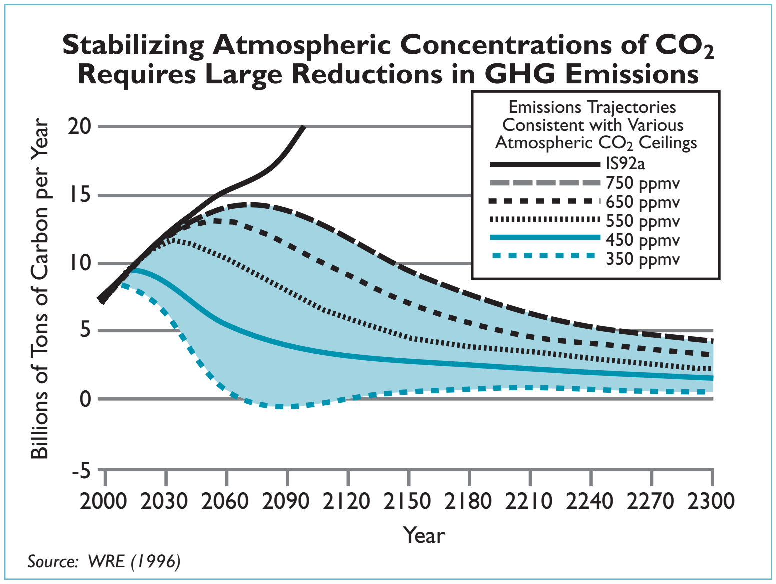


FIGURE 2-8. There are multiple pathways to reaching stable atmospheric concentrations of CO_2.

Human needs—diffusion of innovative technologies to enhance global modernization, rural electrification, urban quality of life, and universal access to education

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

Electricity has a crucial role to play in each of these categories. The Roadmap participants believe that electricity-based technology can and must be harnessed to improve the lives of billions of people. It is arguably the most critical infrastructure for economic development. Moreover, since it provides the only practical means to harness and deliver clean energy on a large scale, its role in environmental protection will only grow larger over the next 50 years.

Achieving Universal Global Electrification

Although electricity has been extended to over 1.3 billion people over the last 25 years, this rate of expansion has not kept pace with global population growth, and under current trends, 90% of population growth in the next 50 years will be in the world's poorest nations. The Roadmap participants have embraced the idea of a "2+ Percent Solution," an across-the-board 2% per year improvement in a broad range of factors, ranging from emissions reduction to resource utilization and agricultural yield.

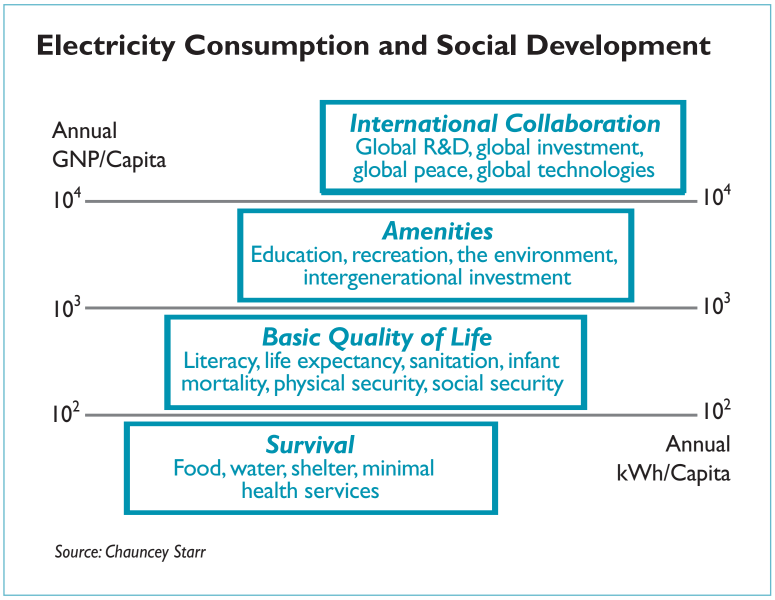


FIGURE 2-9. Many people are trapped in the "survival" development category; electrification could help.

Further evaluation suggests that, while 2% per annum is an adequate rate of improvement in the developed world, at least a 3% annual rate of improvement will be needed in the developing world. This would meet the Roadmap goal of providing 1,000 kWh per person per year to the more than 3 billion people in 2050 who would otherwise be subsisting well below that level under current rates of global electrification. Global data indicate a robust relationship between electric power consumption and economic growth, with each kilowatt-hour consumed adding about $3 to the local economy. This suggests that electrifying the world is not only essential to eliminating poverty, but is part of a strategy for "lifting all boats." Additional benefits that accrue from access to electricity are two-fold: first, a fundamental reduction in levels of pollution, both indoor and outdoor; and second, the freeing up of time through the substitution of commercial energy for manual labor. Experience demonstrates that this energy substitution serves to enable education, to increase family stability, and to lower population growth rates in the developing world.

Electrification in the developing regions of the world is covered in considerably greater detail in Chapter 5 of this summary report. Technologies that support electrification are covered in Chapter 3.

Conclusion

The Roadmap participants have reaffirmed the five Destinations of the Roadmap, as first published in 1999. In fact, the Destinations have been remarkably robust in the face of the many changes in the industry and society since the initial release of the Roadmap. This gives confidence in the roadmapping process and indicates that the Destinations can be used as the basis for the next step in the process—the definition of Limiting Challenges and critical capability gaps that provide the framework for detailed R&D planning and program definition. This has been the primary focus and advancement of the Roadmap as presented in this summary report. The Limiting Challenges and critical capability gaps are summarized in Chapter 6 of this report.

CHAPTER 3 TECHNOLOGY BUILDING BLOCKS

The priorities of the Roadmap stakeholders frame the technology vision for the next 50 years. Through 2025, the highest priority is developing and deploying a smart, adaptive power delivery system to improve economic competitiveness and to increase the system's resilience to withstand both attack and natural hazards.

In power production, the top priority for 2025 is to improve and expand the portfolio of clean, commercially viable power generation options. This will increase fuel diversity and provide the tools to better address the climate change issue. In climate management, improved environmental science and predictive tools are urgently needed, as are "bridge technologies" that can help reduce CO_2 emissions during the next two decades, while lower-emitting and more efficient technologies are being developed to meet the needs of the rest of the century.

Looking farther out to 2050, the stakeholder priorities are focused on three overriding goals:

- Universal deployment of the "smart" power delivery system
- Clean, affordable electricity generation options, optimized for both electricity and hydrogen production, for global use
- Resolution of mankind's impact on climate change

This chapter focuses on technologies that will contribute to the achievement of these goals, including the building blocks for an electricity/hydrogen system and low-cost rugged power generation systems that are desperately needed for the developing world.

A key challenge for the power industry is developing and demonstrating the fundamental building blocks of tomorrow's power infrastructure, which include:

- A "smart" power delivery system
- More energy-efficient end-use technologies (such as hybrid electric vehicles and more sophisticated industrial systems)
- Cleaner and more cost-effective generation options (such as advanced coal, nuclear, and renewables)
- CO_2 capture and sequestration solutions
- Clean and cost-effective hydrogen production, transportation, and storage technologies

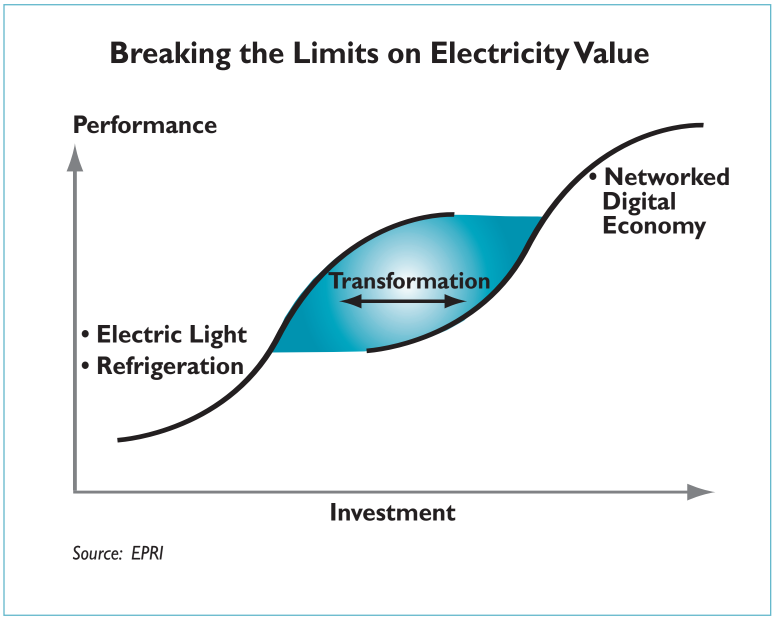


FIGURE 3-1.
The smart power system is an integral part of the networked digital economy.

Outlook for the Smart Power Delivery System

The ultimate force pulling the electricity sector into the 21st century will likely be the technologies of electricity demand—specifically, intelligent technologies enabling ever-broader consumer involvement in defining and controlling their electricity-based service needs. As long as consumer involvement is limited to the on/off switch and time-of-day pricing, the commodity paradigm will continue to dominate the business and require regulation to protect a relatively weak consumer from cost-constrained suppliers. It is important to remember that supply and demand in the electricity industry still rely on the same system design and much of the same technology in use since the dawn of electrification. This is a remarkable record of performance, but one that can no longer be sustained through merely evolutionary changes in the status quo.

Historically, the power delivery issues of security, quality, reliability, and availability (SQRA) have been measured and dealt with in a fragmented manner. In the future, they will almost certainly become a highly integrated set of design criteria to meet the evolving power requirements of consumers. Fortunately, the suite of advanced technologies that can be used to improve the security of the power delivery system can also be used to improve power quality and reliability, and transform the power system to meet the needs of the 21st century.

New dynamic technologies will empower the electricity consumer, stimulating new, innovative service combinations emphasizing speed, convenience, and comfort, with different quality levels and types of electric power. A vigorous, price-sensitive demand response from an increasing class of consumers whose energy choices reflect both electricity prices and power quality will become an integral part of the electricity marketplace.

The shorthand for this new system is the "smart power delivery system," which was conceived of as an electricity/information infrastructure that will enable the next wave of technological advances to flourish. This means an electricity grid that is always on and "alive," interconnected and interactive, and merged with communications in a complex network of real-time information and power exchange. It would be "self-healing" in the sense that it is constantly self-monitoring and self-correcting at the speed of light to keep high-quality, reliable power flowing. It could sense disturbances and counteract them, or reconfigure the flow of power to cordon off any damage before it can propagate. It would also be smart enough to seamlessly integrate traditional central power generation with an array of locally installed, distributed energy resources (such as fuel cells and renewables) into a regional network.

The smart, self-correcting power delivery system will become the conduit for greater use of productivity-enhancing digital technology by all sectors of the economy, leading to accelerated productivity growth rates. The power system will enable new energy/information products and services across the board, and reduce or eliminate the parasitic costs of power disturbances characteristic of the U.S. economy today.

Digital technology will allow price signals, decisions, communications, and network intelligence to flow back and forth through the two-way "energy/information portal."

The Energy/Information Portal

To complete the picture, digital technology will also be able to open the industrial, commercial, and residential gateways now constrained by the meter, allowing price signals, decisions, communications, and network intelligence to flow back and forth through the two-way "energy/information portal." The portal will provide both the physical and logical links that allow the communication of electronic messages from the external network to consumer networks and intelligent equipment. For consumers and service providers alike, this offers a tool for moving beyond the commodity paradigm of 20th century electricity service. It will complete the transformation of the electricity system functionality, and enable a set of new energy information services more diverse and valuable than those available from today's telecommunications industry.

Some of the specific capabilities of the energy/information portal include:

- Advanced pricing and billing processes that would support real-time pricing
- Consumer services, such as billing inquiries, power quality, service calls, outage and emergency services, and diagnostics
- Connections to other information services (Internet, banking, entertainment, etc.) and to other energy sources (gas, oil, hydrogen)
- Information for developing improved building and appliance standards
- Consumer load management through sophisticated on-site energy management systems
- Easy "plug-and-play" interconnection of distributed energy resources
- System operations, including dispatch, demand response, and loss identification
- Load forecasting and long-term planning
- Green power and other targeted marketing and sales opportunities

These functions have the potential for dramatically improving the reliability and productivity of the electricity supply and delivery functions. In addition, they can stimulate productivity improvements for the end-use consumer.

The end user also stands to gain from digital technology advances. The growing trend toward digital control of processes can enable sustained improvements in worker productivity for nearly all industrial and commercial applications. The growth in end-use electrotechnologies networked with system controls will afford continuous improvements in user productivity and efficiency.

Energy/information companies face some significant challenges in developing and commercializing portal systems. Among the challenges are:

- The lack of standards and protocols for both "in-building" consumer equipment and external networks
- The need to deal with evolving systems on both sides of the meter
- Poor understanding of market needs and wants

A research and development program is needed to deal with these challenges. Some of the key elements of the portal research initiative now underway through the EPRI-affiliated Electricity Innovation Institute, include:

- **A common application language widely accepted by the utility industry and product vendors.** Lack of a common application language has hampered portal development due to the perceived risk of market fragmentation.
- **Interoperability and interface standards.** Besides the common applications language, there will be other interfaces in the system that will be common to multiple functional areas. A consistent set of standards for these interfaces will accelerate the development and deployment of consumer portals.
- **Tools for real-time pricing and load response.** These tools speak to a universal need and will be among the first portal applications.
- **Modular electric meters.** It's impractical for a single vendor to address all portal market needs. Moreover, market needs will change over time, creating an opportunity for periodic upgrades of the portals. A flexible, modular approach to developing meter interfaces will allow "plug-and-play" access to advanced meter capabilities.

Capabilities of the Smart Power Delivery System

Enabling the digital economy of the future will require a smart power delivery system that links information technology with energy delivery, thus assuring business continuity. The concept of the smart power delivery system includes automated capabilities to anticipate and recognize problems, find solutions, and optimize performance. The basic building blocks are advanced sensors, faster-than-real-time data processing and pattern recognition software, and solid-state power flow controllers.

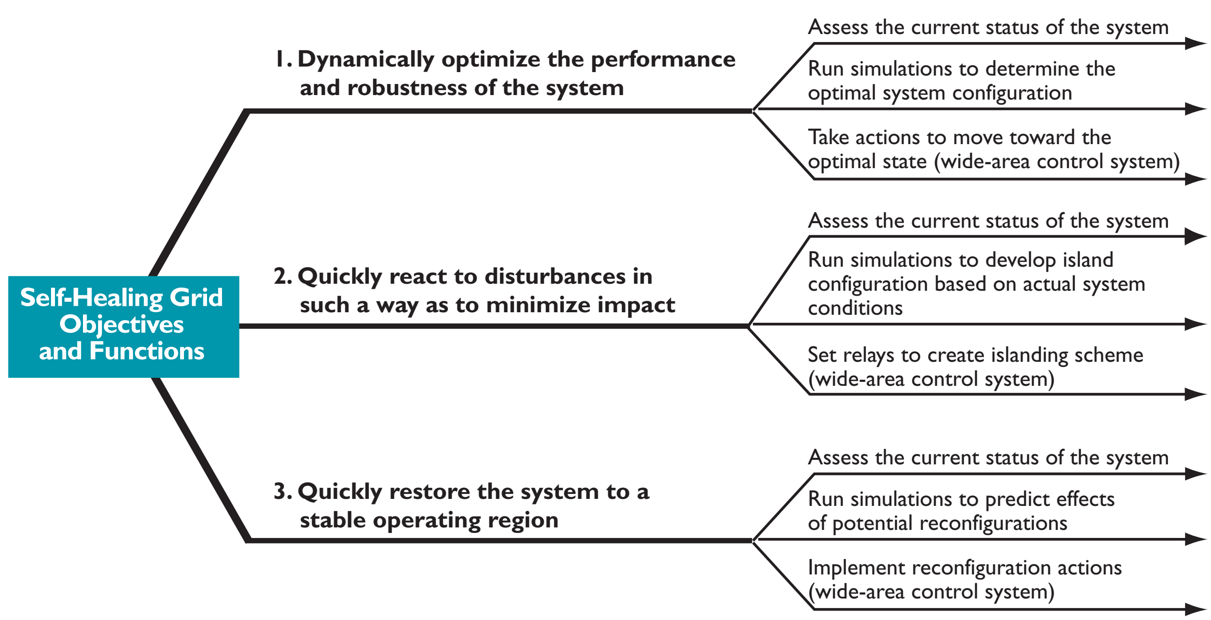
These technologies can reduce congestion, react in real time to disturbances, redirect the flow of power as needed, and automate the operation of the system. As shown in Figure 3-2, there are three primary objectives of the smart delivery system:

Optimize the overall performance and robustness of the system—A wide array of sensors will monitor the electrical characteristics of the system (voltage, current, frequency, harmonics, etc.) as well as the condition of critical components, such as transformers, feeders, circuit breakers, etc. The system will constantly "fine-tune" itself to achieve an optimal state, while monitoring for potential problems that could lead to disturbances. When a potential problem is detected and identified, its severity and the resulting consequences will be assessed. Various corrective actions can then be identified and computer simulations run to study the effectiveness of each action. When the most effective response is determined, a situational analysis will be presented to the operator, who can then implement the corrective action very efficiently by taking advantage of the grid's many automated control features, such as dispatch control of distributed resources and optimization of solid-state power flow controllers. In particular, incorporating distributed energy resource and renewable generation into grid functionality can prove to be a substantial asset to reliability.

Minimize the impact of disturbances—When an unanticipated disturbance does take place on the system, it must be quickly detected and identified. An intelligent islanding or sectionalizing scheme can be activated instantaneously to separate the system into self-sustaining parts to maintain electricity supply for consumers according to specified priorities, and to prevent blackouts from propagating, as happened in the Northeast power disruption of August 2003.

FIGURE 3-2. The self-healing grid is an important "building block" of the smart power delivery system.

Three Primary Objectives of a Self-Healing Grid, Each Supported by Three Functions That Require Technology Development



Source: EPRI

Restore the system after a disturbance—Following a system reaction to a major disturbance, actions will be taken to move the system toward a stable operating regime. To do so, the state and topology of the system need to be monitored and assessed in real time, allowing identification of alternative corrective actions and assessment of the effectiveness of each by look-ahead computer simulations. The most effective actions would then be implemented automatically. When a stable operating state is achieved, the system would again start to self-optimize.

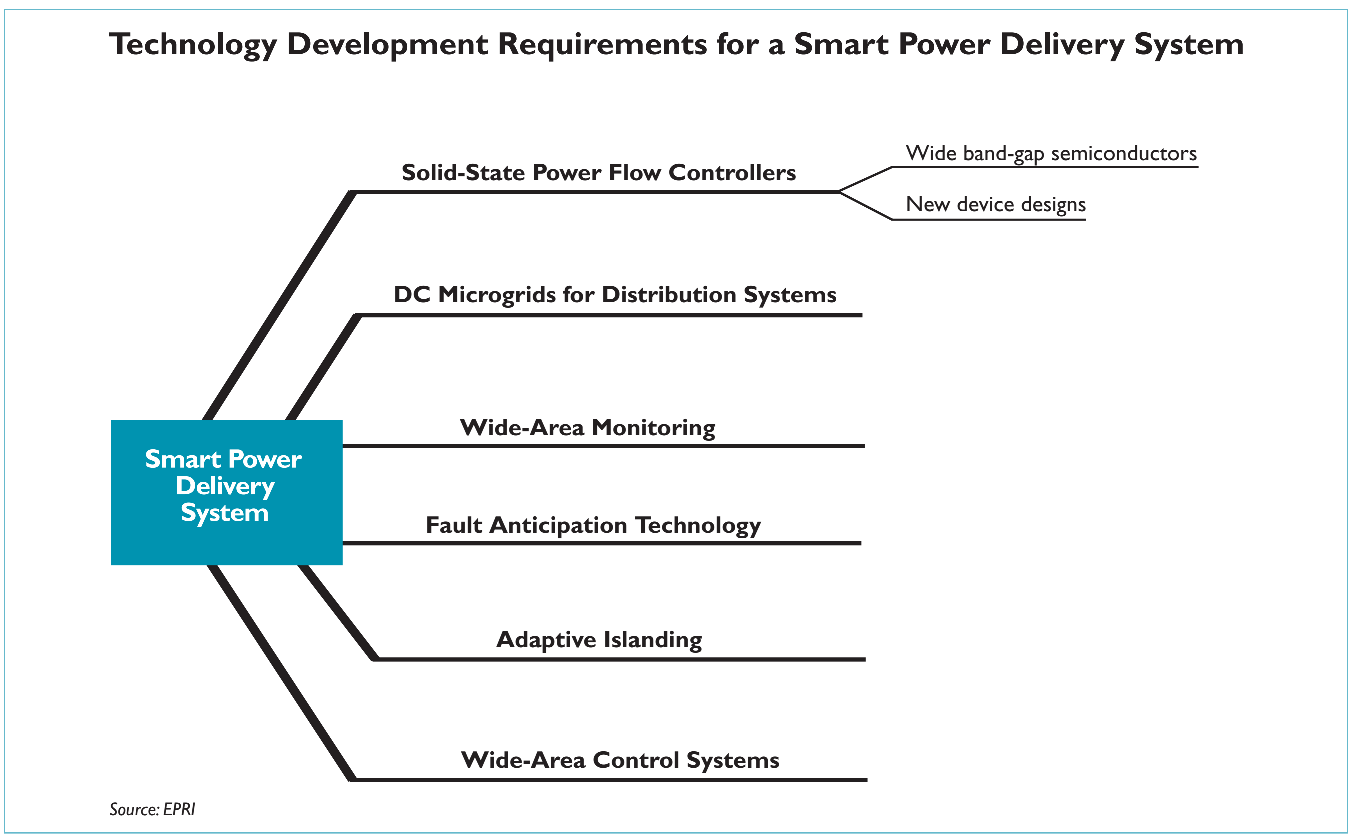
Meeting these objectives will be an iterative process with optimizing system operation being the primary objective during normal operation. When a disturbance occurs, the operating objectives move from reacting to restoring and, finally, back to optimizing. The smart power delivery system is thus said to be "self-healing."

Technology Requirements for the Smart Power Delivery System

Some of the key technologies that will be needed to implement a smart, self-healing grid are summarized below.

Real-time wide-area monitoring system—Elements of the real-time wide-area monitoring system are already in operation on both the transmission and distribution system.

FIGURE 3-3. The smart power delivery system depends on the success of many R&D efforts.

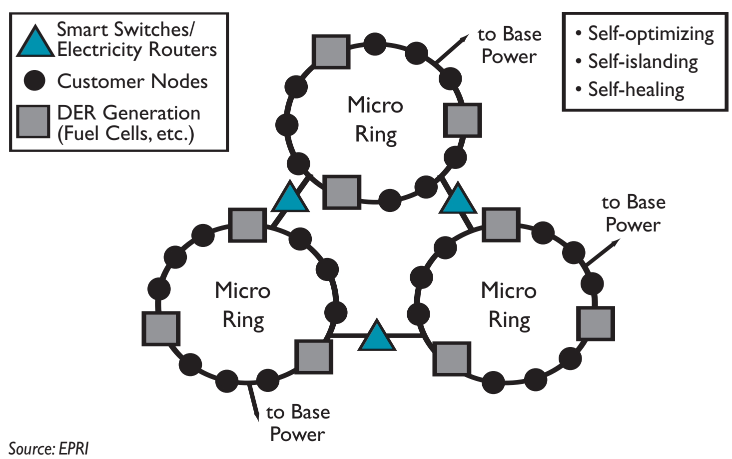


For example, the Wide-Area Measurement System (WAMS), originally developed by Bonneville Power Administration (BPA), is a system based on high-speed monitoring of a set of measurement points and the generation of operator displays based on these measurements. WAMS provides a strong foundation on which to build the real-time wide-area monitoring system required for the self-healing grid. The system architecture will define the data, communications, and control requirements for the self-healing grid.

Anticipation of failures and disruptions—Substantial work has been done by EPRI and others in determining the root cause of failures in critical components, such as transformers, cables, surge arresters, etc., and in developing monitoring and diagnostics systems for these components. The next step is to develop fault anticipation technology that will provide early warning and failure forecasting. This technology (analogous to automated "fly-by-wire" system standards used in high-performance military and commercial aircraft) will improve system state estimation from a delayed reactive system with response times on the order of minutes to an anticipatory system, capable of calculating several cycles ahead of time. Work on fault anticipation for overhead distribution systems is currently underway. Some failure prediction work has already been performed; however, more is needed.

Adaptive islanding—Following a major grid disruption, initial reaction will focus on creating self-sufficient islands in the power grid, adapted to make best use of the network resources still available. To achieve this aim, new methods of intelligent screening and pattern extraction will be needed, which could rapidly identify the consequences of various island reconnections. Adaptive load forecasting will also be used to dispatch DER, including generators and mobile substations, in anticipation of section reconnection and to help stabilize the overall transmission-distribution system.

The Smart Grid Connects Distributed Energy Resources Through Microgrids



Source: EPRI

FIGURE 3-4. "Plug-and-play" connectivity for distributed energy resources (DER) is just one benefit of the smart grid.

Wide-area control systems—Once predictions have been made about the effectiveness of various potential control actions, the identified actions need to be carried out quickly and effectively. Achieving this goal will require automating many operations that will make human intervention on both transmission and distribution systems more efficient.

Solid-state power flow controllers—By acting quickly enough to provide real-time control, solid-state power flow controllers, such as FACTS and Custom Power devices, can increase or decrease power flow on particular lines, alleviating system congestion. In addition, these controllers can enhance system reliability by counteracting transient disturbances almost instantaneously, allowing the system to be operated closer to its thermal limits. The major development challenge for solid-state power flow controllers now is to reduce the cost of these systems to achieve the needed widespread utility use.

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 site, and connect distributed generation systems to the grid without the need for costly individual 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 independently using distributed generation and storage. On distribution networks, DC cables could be placed in the same ducts as gas and water pipes, because they will not induce AC currents in the other pipes and ductwork. 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, single point converter technology should become cost-effective by about 2008–2010, even without including the end-use device savings.

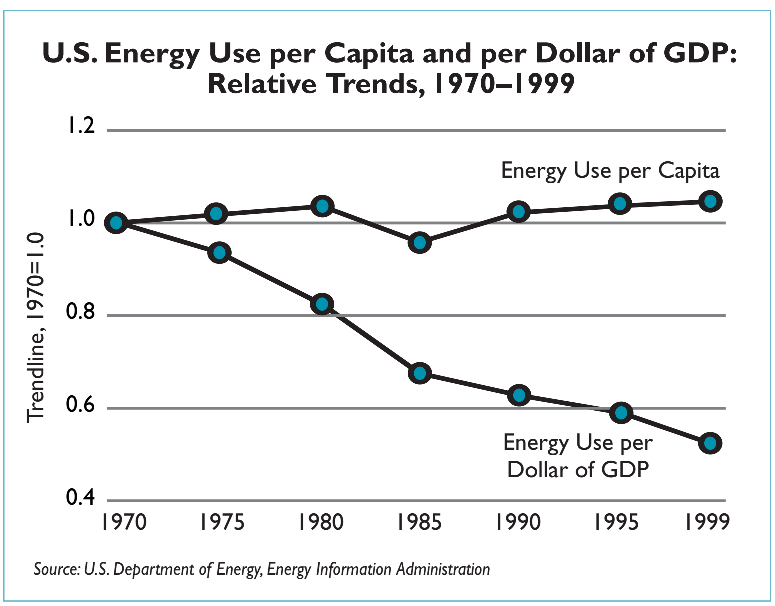


FIGURE 3-5. Greater energy efficiency means less energy is needed to power economic growth.

Superconducting power delivery systems—One emerging distribution option uses a high-temperature superconducting 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. Superconducting DC loops could provide premium power for large urban regions, comparable to today's networked distribution systems that serve mainly downtown areas. In the near term, superconducting technology could also increase the carrying capacity of distribution feeders. Superconducting DC loops could become a common feature in distribution systems by 2020. A longer-term variation of this concept uses liquid hydrogen as the refrigerant in the superconducting loop. The customer would then have the option of using hydrogen as an energy carrier and balancing the on-site use of hydrogen and electricity to optimize energy usage. Additional information on this concept is provided later in this chapter.

Outlook for Energy Efficiency

The development of the smart power delivery system holds enormous potential for improving the efficiency of energy use. First and foremost, it opens the door to a strong demand-side response to price signals, reducing the need for peak generation, improving the use of capital, and affording better asset management throughout the entire energy chain, all with positive repercussions for the environment.

Secondly, it paves the way to more rapid introduction of new energy-efficient technology in the form of downloadable software, replacing fixed-efficiency hardware. The beauty of an intelligent energy system is that it affords the prospect for continuous improvements in energy efficiency by taking advantage of the opportunities that a digital economy provides.

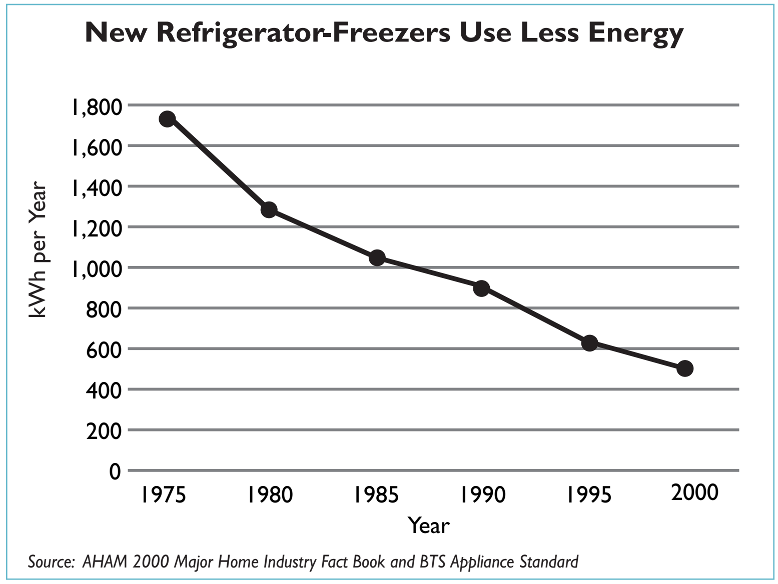


FIGURE 3-6. Numerous appliances have become more energy efficient—but there is room for significant improvements.

However, funding for energy-efficient technology development has declined precipitously and the incentives for investment in end-use technology today are insufficient to restore the needed technology development effort. The Roadmap stakeholders encourage a more robust and balanced national energy R&D program, with demand-side and supply-side components. In particular, they recommend more extensive R&D programs designed to provide the digital economy of the future with highly energy-efficient and reliable technologies. This opens the opportunity to optimize the smart delivery system to provide an intelligent conduit for new energy-efficiency ideas, methods, and technologies.

Some of the promising avenues identified by the Roadmap participants include:

- **Load management technologies**—There is a need to develop communication protocols and electronic equipment, such as direct digital control systems, for load management. These systems can link power, data, and communication equipment to provide real-time control of integrated systems that integrate HVAC, lighting, and process systems with on-site energy generation and storage systems.
- **Industrial motor systems** represent the largest single electricity end use in the American economy. Industrial electric motor systems and motors used in industrial space heating, cooling, and ventilation systems use roughly 25% of all electricity sold in the U.S. Research is needed to develop motors that use energy more efficiently and are able to ride through a variety of power quality disturbances. Also needed are better control systems that enable motors to follow the load more closely by adjusting the amount of power delivered to the motor on a continuous basis.

- **New transportation options**—Improving the energy efficiency of all modes of transport would provide environmental benefits while conserving and eventually replacing oil in the transport sector (see Figure 3-7). Future electric technologies offering major advances include hybrid electric vehicles that plug into the grid. These vehicle designs use batteries that are more powerful than those in current commercial hybrids. Over the long run, the grid-connected designs may incorporate hydrogen fuel cell power plants as mobile distributed energy sources.
- **Lighting** accounts for 20–30% of all commercial electricity use in the U.S. Research is needed to develop lighting systems based on novel lighting sources, such as ultraviolet vertical-cavity surface-emitting lasers (UV VCSEL) and light-emitting polymers (LEPs). These technologies produce higher output levels per unit of energy that can be precisely managed under a variety of control scenarios, resulting in reduced heat generation within the lighting system.
- **HVAC** systems and components that use electricity more efficiently and do not rely on environmentally harmful refrigerants need to be developed. In addition, enhanced control technologies are needed to enable HVAC systems to better follow air conditioning loads and to allow the seamless integration of HVAC and advanced thermal energy storage systems.

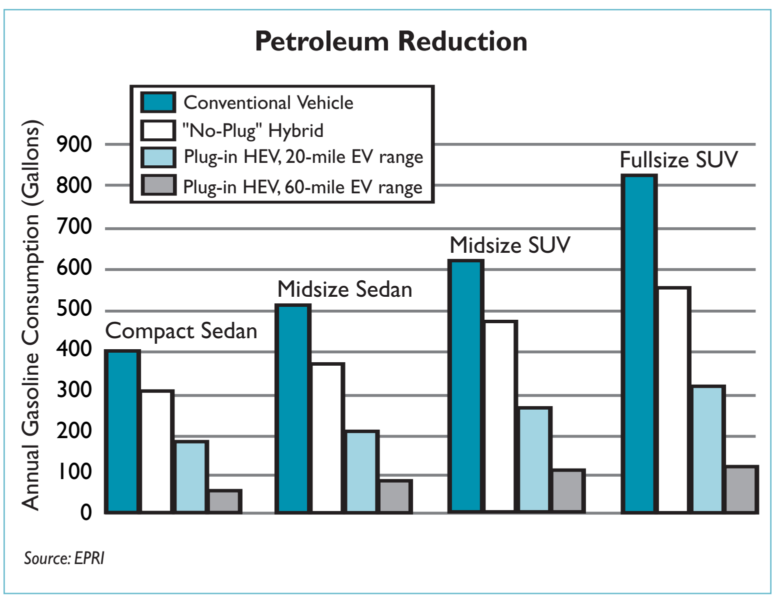


FIGURE 3-7. Hybrid electric vehicles (HEV) can reduce global dependence on oil.

- **The process industries**, advanced manufacturing, and information technology all make special demands on the power system and are the subject of programs sponsored by industry and the U.S. DOE to reduce energy requirements. One example is the development of inert anodes for electricity-intensive aluminum smelting. Conventional smelting technology uses consumable carbon anodes inserted into a molten salt bath in which aluminum oxide is electrochemically reduced to aluminum metal. The anode reaction produces CO_2, which is released to the atmosphere. Inert anodes, now under development, would replace the carbon anodes with an oxidation-resistant material. The result would be the elimination of CO_2 production from this process and an energy saving of approximately 25%.
- **Steelmaking**—A second example of emerging productivity-enhancing manufacturing is direct steelmaking through the combination of microwave, electric arc, and exothermal heating. This approach could mean a great change from current steelmaking technology. The new technology, being developed with support from the U.S. DOE,

will produce molten steel directly from a shippable agglomerate consisting of iron oxide fines from ore concentrates, powdered coal, and fluxing agents, such as ground limestone.

The technology is expected to save up to 25% of the energy consumed by conventional steelmaking by replacing blast furnaces and basic oxygen furnaces with more efficient technologies. The new process will also reduce SO_X and NO_X emissions, reduce waste and emission control costs, and reduce capital cost.

The project is based on the capability of microwaves to heat the agglomerate to temperatures sufficiently high for the rapid reduction of the iron oxide component (consisting of crushed and ground iron ore) by the coal. The products are then heated to steelmaking temperatures by the electric arc, assisted by the exothermic reaction of coal with oxygen. The microwave and electric arc heating will require excellent power quality to maintain the process control parameters for the steel product.

- **Chemical Processes**—There are many opportunities to apply new technologies to reduce the capital and operating costs and to improve environmental performance of the highly energy-intensive chemical industry. Many of the emerging technologies consist of improved processes that work at lower temperatures to reduce energy requirements or make more effective use of catalysts.

  One example of the former is the development of an oxidative cracking process to produce ethylene from ethane. Known as catalytic autothermal oxydehydrogenation (CAO), this process does not require a furnace and does not produce flue gas. Compared with the existing means of ethylene production (using a steam cracker at high temperatures), CAO would be dramatically more energy efficient as well as more environmentally sound. In short, CAO would reduce the formation of NO_X, lower CO_2 production by a factor of 10, and reduce the by-product stream. It also has the potential for significantly lower energy requirements by 2020. Moreover, one of the by-products of CAO would be a fuel gas containing methane, hydrogen, and carbon monoxide. This fuel gas could be synthesized to produce hydrogen, a critical input to the electricity/hydrogen economy described later in this chapter.

  This approach may at some time compete with a different approach—microwave synthesis of ethylene. This process uses tuned microwaves to selectively energize and break key chemical bonds in ethane to form ethylene. It offers a large performance improvement over conventional technology, and nearly eliminates the toxic by-product stream. While this technology offers a substantial performance advantage, oxidative cracking is expected to be more familiar to workers in chemical plants and may emerge as the process of choice.

  An example of improved catalysts is the development of nanoscale catalysts based on molybdenum and tungsten carbides. These catalysts are supported on a substrate of carbon nanotubes and nanorods. They maintain thermal stability and high surface area, even under severe operating conditions, offering the performance of platinum at a fraction of the cost.

- **Electronics**—The energy implications for the electronic and semiconductor industries differ strongly from the situation in primary metals production. Although power quality and reliability are important in both industries, the impact of power quality problems, especially those of short duration, are much larger for the semiconductor sector in terms of lost production and equipment damage. Specifically, the semiconductor fabrication process is extremely sensitive to power quality events of very short duration (even as brief as a few milliseconds), whereas aluminum smelters, for example, can recover from an outage lasting several hours, as long as the melt does not freeze. (Note, however, that major damage will occur if the liquid does solidify.) Right now, many semiconductor manufacturers are reducing building energy loads through lighting upgrades and HVAC enhancements, adding monitoring systems to assure that critical equipment is operating under optimal conditions, reducing peak load requirements, and improving reliability and power quality by adding on-site generation and storage systems and other distributed energy resources.
- **Internet Data Centers**—One area in which substantial energy efficiency improvements appear possible is that of Internet data centers. These facilities are the "brains" of the Internet and are responsible for the transmission and delivery of billions of messages daily. The cost of the power systems, including backup generation, comprises as much as two thirds of the total cost of large Internet data centers. Recent studies have suggested that there are specific opportunities to reduce the energy requirements of Internet data centers. These opportunities include the development of more energy-efficient processor chips to reduce the heat load in the buildings, high-efficiency power supplies that maintain efficiency over a wide range of loads, and high-efficiency fluid cooling systems that use heat pipes to isolate the fluid from the electronic components.

Outlook for the Portfolio of Generation Options

Changing from a global system where more than 85% of the energy used releases CO_2 to a system where less than 25% is released requires fundamental improvements in technology and major capital investments. A robust portfolio of advanced power generation options—fossil, renewable, and nuclear—will be essential to meet the economic aspirations of a rapidly growing global population.

The portfolio strategy offers the greatest flexibility and resiliency in meeting the uncertainties of the future, as well as the opportunity for different regions of the world to adjust the portfolio balance to suit their circumstances. 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 factor will be the growing pressure to internalize the environmental costs of fossil energy, which will increase the relative importance and attractiveness of renewable and nuclear energy.

As an example, if a decision were made to cap atmospheric CO_2 concentrations at no more than 550 ppm (twice preindustrial levels), a global average emission rate of less than 0.2 kgC/kWh (kilogram of carbon per kilowatt-hour of electricity generation) would have to be achieved by the latter half of the 21st century. With today's technology, the best rates achievable are 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- or near-zero emission carbon alternatives for large-scale global deployment. Such alternatives do not exist today on the scale or at the cost required, although reactor redesigns currently under review by the U.S. Nuclear Regulatory Commission could satisfy this need.

The Interrelationship of Portfolio Options

The diverse portfolio options are interrelated since changing the role of one option has significant implications on the other options and their role in the portfolio.

The Continuing Need for Coal Power

There is widespread recognition among the Roadmap participants of the continuing need for coal, particularly as a long-term transition fuel. One concern, however, is the next generation of coal plants. As the current fleet of fossil plants age and are faced with increasingly stringent environmental requirements, they will become uneconomic. Eventually, the plants will have to be retired and replaced with new technology. There is significant opportunity to improve the efficiencies and environmental performance of coal by "refining" it into clean gaseous fuel or feedstock. The gasification process can provide both high-efficiency power generation and hydrogen. The process is also amenable to carbon capture and sequestration. The U.S. DOE is proposing a "FutureGen" project, which contemplates a $1 billion collaborative undertaking with industry to design, build, and operate an integrated, coal-gasification combined-cycle (IGCC) plant with carbon capture and sequestration and the potential for hydrogen generation.

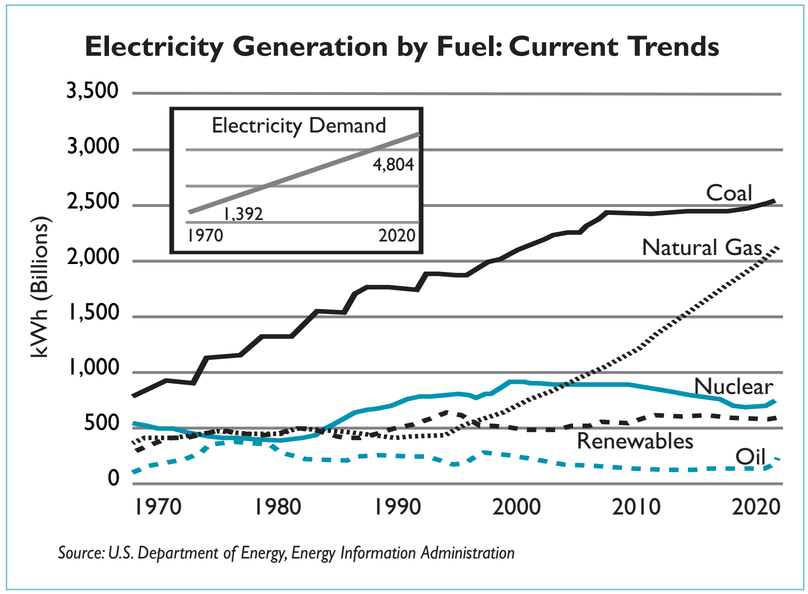


FIGURE 3-8. Coal will remain an important part of the U.S. energy portfolio over the medium to long term.

High-efficiency combustion-based systems are also under development. Operating at steam temperatures of as much as 700°C, advanced coal combustion can meet or exceed the conversion efficiency of today's gasification technology, and offer what may be a less technically risky alternative to IGCC.

Reducing CO_2 Emissions from Electricity Generation

Many options exist—at least in theory—for reducing the net flux (e.g., additions minus removals) to the atmosphere of CO_2 from electricity production, transmission, distribution, and use.

Some Generation "Wild Cards" for the Future

Our ability to predict the future is limited. Technology breakthroughs can appear on little notice, based on historical advances such as the Internet, biotechnology, nuclear energy, and electric power itself. By 2050, there could be completely new ways of generating electricity, despite our skepticism or ignorance of them today. The Roadmap acknowledges this uncertainty, noting examples of future "wild card" technologies such as the following:

Bio-Electricity—Some microorganisms can convert toxic organic compounds, such as toluene, to electricity. They can be used to harvest energy from waste matter, or to clean up subsurface environments contaminated by organic matter. By better understanding how microbes generate and use electrical energy, we may be able to develop new and nonpolluting electricity generation techniques as well as new technologies to decontaminate polluted water and sediment.

Bio-Hydrogen—Many anaerobic organisms can produce hydrogen from organic substances ("bio-hydrogen"), converting carbohydrates to organic acids and hydrogen. To extract the maximum hydrogen from organic molecules, researchers are evaluating a two-stage process—(1) a fermentation reactor with (2) photosynthetic bacterial hydrogen production. The photosynthetic reaction uses the energy from sunlight to completely convert the organic acids to carbon dioxide and hydrogen molecules, releasing essentially all the available hydrogen.

Solar Satellites—Solar satellite power involves very large orbiting solar collectors that could generate very large amounts of electric power and transmit it in the form of microwave energy back to earth. Today, high-voltage solar panels that could handle sunlight during 99% of a 24-hour day, wireless transmitters to beam large amounts of microwave energy, and an "inflatable radiator" to absorb heat in space, are all under development. Although the microwave field strength is relatively low, R&D is needed to assure the safe operation of microwave-based systems. Thus, an economically viable solar satellite-based power system may not emerge until 2025 to 2035 at the earliest.

Fusion Power—Fusion power offers the potential of an almost limitless energy source, but it presents formidable scientific and engineering challenges. Researchers have high confidence that it will be possible to make fusion energy practical. The next phase in fusion power development is the "ITER" machine, which will burn the high-energy plasma to provide a portion of the power needed to operate the device. ITER will focus on detailed experimental campaigns and advanced computer modeling aimed at understanding the physics of a burning plasma machine. Machines such as ITER will provide the basis for the design and deployment of commercial-scale fusion power systems.

Ocean Energy—Because ocean energy is abundant and non-polluting, today's researchers are exploring ways to make ocean energy economically competitive with fossil fuels and nuclear energy. European Union (EU) officials estimate that by 2010, ocean energy sources will generate more than 950 MW of electricity—enough to power almost a million homes in the industrialized world. Ocean energy draws on the energy of (1) ocean waves, (2) tides, or (3) the thermal energy (heat) stored in the ocean.

Solar Towers—Solar towers produce power from a large-scale passive solar collector that feeds trapped heat into a very tall updraft chimney. They consist of a large field of sun-tracking mirrors, called heliostats, which focus solar energy on a receiver atop a centrally located tower. They work by concentrating thermal energy to heat water or molten salt, which, in turn, produces the steam that moves the turbine-generator. Significant R&D is necessary to develop solar tower technologies that will work in regions that are not extremely sunny and that are not excessively costly to manufacture.

The options for reducing net flux include:

- Improvement of efficiency in electricity generation, transmission, and distribution
- Substitution of more efficient end-use electric technologies for less efficient alternatives
- Fuel switching (e.g., from coal to natural gas, which can cut CO_2 emissions nearly in half)
- Development and deployment of advanced, high-efficiency coal generation technologies, integrated with CO_2 capture and storage
- Substitution of non-emitting generation (e.g., renewable energy, nuclear energy) for fossil-fueled generation
- Sequestration of atmospheric CO_2 by changes in land use and forestry practices
- Sequestration of atmospheric CO_2 by chemical reactions and removal in the ocean
- Development of cost-effective direct CO_2 capture and disposal options
- Long-term storage in geological formations and deep underground aquifers
- Use of electric-drive systems to increase transportation efficiency and thereby reduce net CO_2 emissions (e.g., hybrid vehicles, electric vehicles, fuel cell vehicles, and Mag-Lev trains)

Unfortunately, none of these options is a panacea. Some are of limited capacity or are prohibitively expensive; others may require further R&D to advance from theory to commercialization; and some may not enjoy public confidence. Overcoming these and other barriers will require sustained investment in a portfolio of energy technology R&D that creates a stream of increasingly cost-effective technologies over time. However, a steep decline in public and private sector energy R&D funding over the last decade suggests that a considerable amount of time is likely to pass before a new generation of low- or no-carbon energy and transportation technologies are widely deployed. The question then remains: What will form the bridge to the future?

CO_2 Sequestration

Carbon sequestration (i.e., CO_2 capture, transport, and disposal), although commercially available today on a very limited basis, is prohibitively expensive for large-scale use, costing $30 to $70 per ton of CO_2. This would significantly raise the cost of coal-fired power to $60–$80 per MWh. Nevertheless, it has the potential to become a major component of future strategies for mitigating global climate change. For example, in the U.S., depleted oil and gas wells could store about 40 years of CO_2 at today's emission rates. Globally, saline formations have the potential to store hundreds of years of CO_2 emissions. Recent analyses indicate that carbon sequestration could begin to play a major role within a decade of the start of a GHG mitigation initiative, and ultimately could account for more than 40% of all emissions reductions below the IS92a Reference Case in 2100. The wide applicability of carbon sequestration, both within the electricity sector and across other sectors, accounts for the potential prominence of this technology. Within the electricity sector, CO_2

capture technology could be applied in a post-combustion configuration for conventional fossil fuel-fired power plants, incorporated into the process stream of advanced generation technologies such as IGCC, or integrated with natural gas fuel cells.

Next-Generation Nuclear

Nuclear plants already deliver reliable baseload power with the lowest operating, maintenance, and fuel costs among generating options in the U.S., and are highly competitive with new fossil fuel plants in most other countries where such fuels are expensive or not readily available. Potential "carbon taxes" could make nuclear plants competitive in many more situations. All nuclear options face two primary barriers to deployment: high capital costs and uncertain licensing processes. Nuclear Regulatory Commission-certified Advanced Light Water Reactor (ALWR) options are available today, and more certified designs will be available in one to three years, with R&D underway to further reduce construction duration and cost. Accelerating work on high-temperature gas-cooled reactors (HTGR) is needed to take advantage of this design's higher plant efficiency and modularity to bring its capital costs closer to the competitive range. HTGR designs are also well suited for integrating hydrogen production with electricity generation. Both ALWR and HTGR designs have achieved major strides in nuclear safety. Both designs rely on the once-through fuel cycle, the most proliferation-resistant fuel cycle option. Continued progress on licensing a high-level waste repository at Yucca Mountain will help address other important public concerns.

For the longer term, an international initiative is developing reactor concepts and designs for "Generation IV" power plants. Generation IV plants go beyond current Generation II and III plants in the areas of:

- Promoting a sustainable electricity supply
- Making nuclear energy competitive with alternate generation options
- Improving safety and reliability
- Proliferation resistance and physical protection

The international Generation IV initiative is evaluating several designs as part of a roadmapping exercise that will lay the groundwork for nuclear energy throughout the 21st century.

Although spent fuel management is not a major near-term technical challenge, it does present long-term challenges under scenarios that include a major global expansion of nuclear energy. The long-term issue is nuclear fuel cycle optimization. Today's scientifically preferred solutions (centralized above-ground storage and deep geologic repository) may evolve to other solutions, such as recycling spent fuel. In every scenario and solution to this issue, centralized storage is required, whether above or below ground, and whether permanent or retrievable. A major expansion of nuclear generation will inevitably focus much more attention on nuclear fuel supply consumption and spent fuel management—on a global basis. Each nation using nuclear energy will need to develop its own capability to properly manage spent fuel and/or collaborate in regional or global spent fuel management programs that effectively address health, safety, nonproliferation, and material control issues. These issues, however, should not have a detrimental effect on the near-term deployment of new plants using current technology and regulations.

Renewables

Another option for reducing CO_2 emissions over the medium and long term is electricity generation via renewable energy resources. Because of the many environmental issues associated with hydropower (which is the predominant form of renewable generation in the U.S.), non-hydro options offer the greatest potential for future growth. To date, the market penetration of these technologies has been limited primarily because of (1) high capital and maintenance costs, (2) resources that are geographically isolated, and (3) intermittent production (e.g., only when the sun shines or wind blows), which hampers dispatchability and energy management planning. Nonetheless, the combination of technical advances and government incentives—particularly for wind—has new capacity being added at a rate of more than 5% per year.

As intermittent renewables play an increasing role in the electricity supply system, grid operators face added challenges in assuring electrical stability and reliability. Meeting this challenge will require smart grid implementation and:

- Integrating storage media with intermittent generation sources
- Developing standards for connecting DER to the grid
- Improving the ability of the electric grid to better accept dynamic loads through electronic control
- Creating models that better predict the output of intermittent resources by improving short- and long-term weather forecasting
- Commercializing new wind turbine designs that better capture energy from light winds
- Developing novel direct-conversion solar technologies, both photovoltaic and thermal

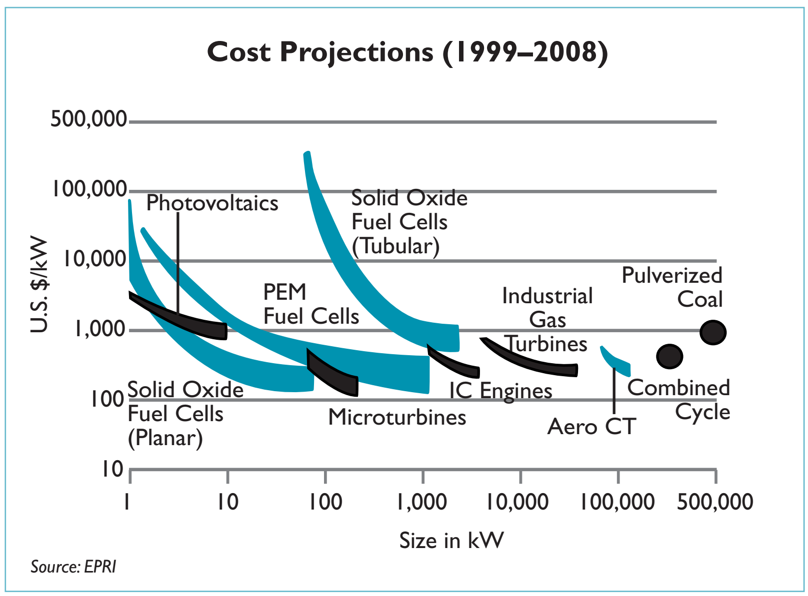


FIGURE 3-9. Distributed resources can address a wide spectrum of power capacity needs.

Given sustained investment in R&D, added renewables could reduce the CO_2 intensity of the U.S. generating fleet by 5% over the next 10 years. By 2020, this figure could rise to 10%.

Distributed Energy Resources

Distributed energy resources (DER), in the context of this broader transformation, is becoming an integral asset in the electricity supply system. As DER grows, it could

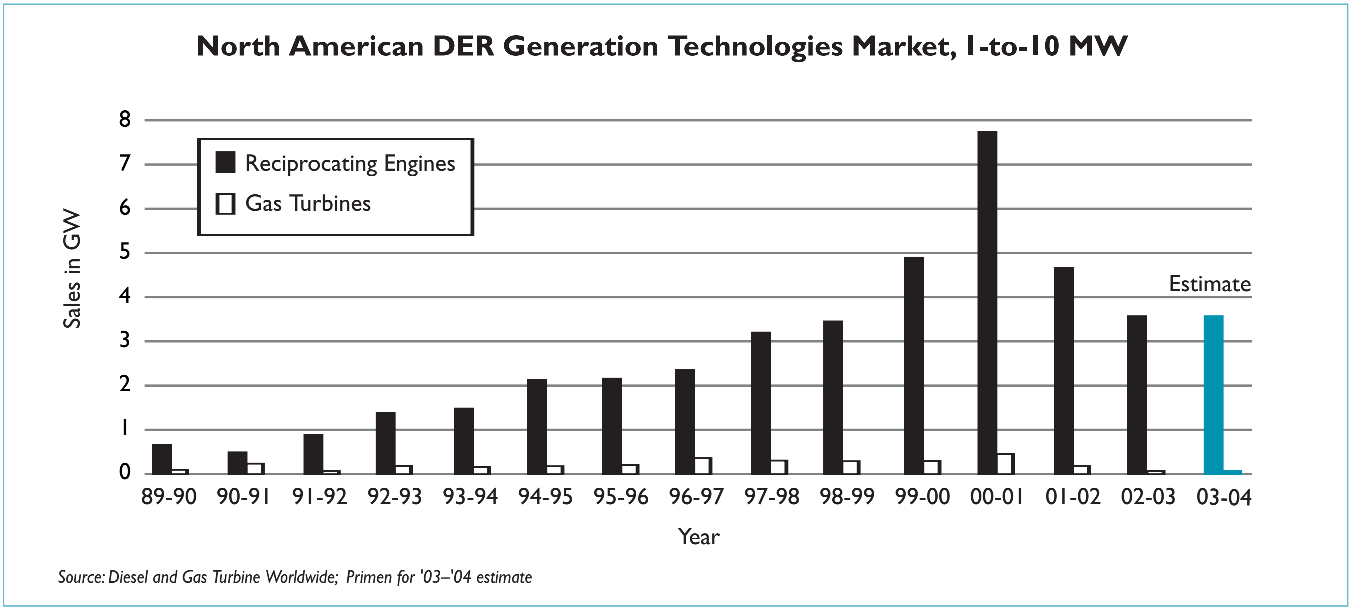


FIGURE 3-10. Commercial and industrial sectors will drive the adoption of DER to improve reliability and improve power quality. The dollar value of sales is expected to quintuple between 2003 and 2010.

fundamentally change the relationship between power supplier and the consumer and, in time, the network architecture of the distribution system. The system would enable two-way flow of power and communication. It could also enable competitive markets for a broad range of distributed services. Increasingly sophisticated consumers who value the ability to choose among unbundled services will finally understand that electricity is embedded in virtually all goods and services. Technology advances will set the stage for the emergence of a new generation of higher-margin energy services, including power quality and information-related services.

Broad-scale application of DER holds promise for relieving constraints in generation, transmission, and distribution capacity and enhancing grid security. Because many DER technologies operate quietly and with few emissions, they may be easier to site in metropolitan areas, where the alternatives for upgrading T&D capacity are very expensive. If needed, DER technologies can also operate independent of the grid or can power special-purpose networks, such as DC microgrids.

The portfolio of DER generation technologies includes reciprocating internal combustion (IC) engines (500 kW–5 MW), small combustion turbines (5–50 MW) and even-smaller microturbines (kW-scale), and various types of fuel cells. Sometimes photovoltaics, small wind turbines, and other renewables are also considered DER technologies. Commercial DER storage technologies include batteries and capacitor banks. Advanced and novel DER concepts under development include Stirling engines, various generating technology hybrids, flywheels, "ultracapacitors," and superconducting magnetic energy storage systems. Related R&D is addressing DER-specific power conditioning equipment.

Research over the intermediate term is focused on the development and demonstration of advanced DER technologies, particularly "hybrid" systems, such as those integrating high-efficiency fuel cells with advanced microturbines. The Roadmap assigns high priority to increasing the power density of solid oxide and proton exchange membrane fuel cells and reducing their cost to less than $100/kW. Much of this work will provide a foundation for the long-term goal of commercializing ultra-high efficiency, cost-effective DER options. Overall, DER has the potential to significantly change the configuration and control of today's power delivery systems.

Outlook for the Electricity/Hydrogen Economy

Policymakers and the technical community are exploring approaches to use hydrogen as an energy carrier that complements electricity. Both hydrogen and electricity are clean at the point of use, are easily converted to one another, and can be derived from a variety of domestic primary energy sources. Potential uses include both stationary and vehicular power as well as energy storage. Hydrogen's greatest value appears to lie in scenarios driven by energy supply security and climate change, especially when used as a motor fuel, or in other distributed applications. In either case, hydrogen should integrate well with electricity. Electricity is more flexible and less costly, while hydrogen is easier to store and increases the capacity factor for expensive generation infrastructure.

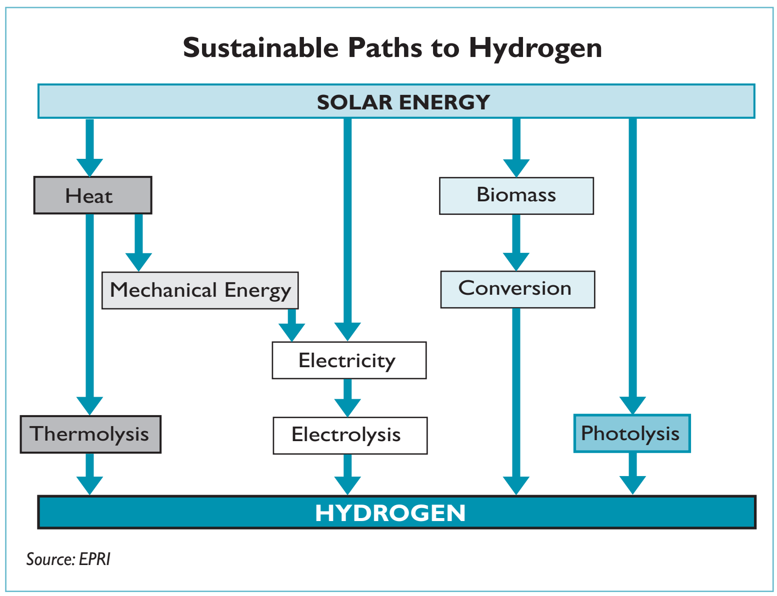


FIGURE 3-11. A workable R&D strategy must consider multiple approaches to hydrogen production.

The Electricity/Hydrogen Vision

The Roadmap participants envision a future in which, by 2050, half of the nation's electricity generating capacity emits no carbon dioxide and half of all transportation vehicles are fueled by hydrogen. Large, centralized hydrogen generation plants could be placed at network nodes/hubs to serve broad regions. The nodes would store and deliver hydrogen, with smaller, distributed hydrogen plants at distribution feeders or hubs to help meet peak and intermediate loads.

This vision requires development of an energy infrastructure that can support expanded production, delivery, storage, and use of hydrogen energy. Construction of this infrastructure will require massive efforts and resources, resulting in evolution of the electricity/hydrogen economy over many decades. Storage weight and volume reductions, mass production of fuel cells, construction of the necessary infrastructure, and expanded use of portable and distributed power generation devices will sustain the momentum toward an electricity/hydrogen economy. Early glimpses of this vision can already be seen in pilot programs underway in a few U.S. locations and several other countries. But there are formidable technological and economic challenges that must be addressed at every stage in the hydrogen energy chain, from production, to transport and local delivery and storage, to end use.

A related concept (called Super Grid) is based on integrating a superconducting transmission or distribution cable with a hydrogen delivery system. Here, liquid hydrogen cools the superconductor, as well as being an energy carrier. The customer can independently vary the amounts of hydrogen and electricity used, based on price variations, convenience factors, importance of reliability and storage concerns, and so forth.

An Uncertain Portfolio Option

The future large-scale use of hydrogen to carry energy is not without controversy. There are many unsolved barriers to the development of technologies and systems that would permit a viable electricity/hydrogen economy for 2050 and beyond. Acknowledging this uncertainty, the Roadmap envisions hydrogen as a promising future possibility rather than an inevitable future. However, its potential value in energy efficiency, global emissions reduction, and energy resource conservation justifies serious study and development efforts.

The cost of producing hydrogen is substantially higher than that of primary energy sources, such as coal or gas. These costs are driven by production of hydrogen from water (e.g., electrolysis) or from fossil feedstocks (e.g., steam reforming of methane, or coal gasification). Likewise, storage adds to the overall cost, because of the need for technologies to compress the gas, liquefy it, or convert it to a solid form such as metal hydrides. The ultimate fuel cycle energy efficiency gains and emissions savings of hydrogen are uncertain. But its potential appears to be great and efforts to overcome the obstacles are amply justified though not yet committed.

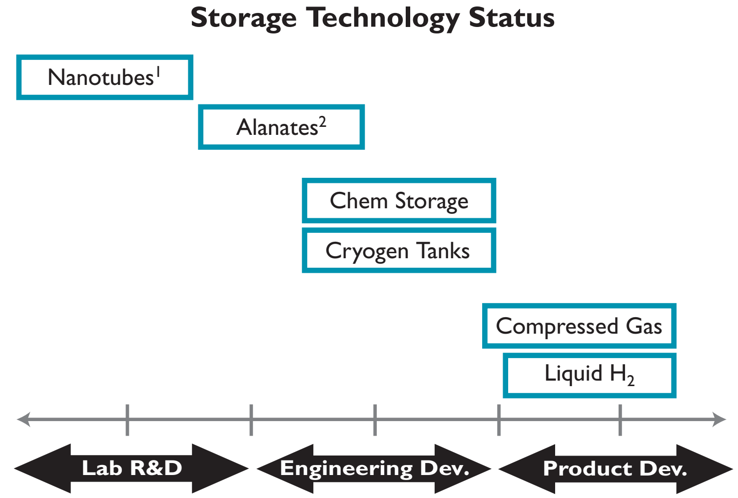
Hydrogen Production Technology

The cleanest way to make hydrogen is to use electricity from renewable or nuclear sources to electrolyze water into its component gases. The cost of this approach is now about four times higher than that of producing hydrogen from fossil energy sources. This indicates that near-term production of hydrogen is likely to focus on gasification of coal or steam reforming of methane, with sequestration of the CO_2 produced. This transition will enable the development of a hydrogen infrastructure and early applications while work continues to reduce the costs of electrolysis. DOE has begun a "nuclear-hydrogen" initiative that would demonstrate a high-temperature gas reactor with the capability to split water using an emission-free sulfur iodine process. The high-temperature requirements of this process are presenting engineering challenges, but the payoff, if successful, will be hydrogen production at competitive prices.

The impetus for change is coming from both the private and public sectors. Companies and governments worldwide are now investigating select applications with the view that hydrogen could someday largely replace carbon-based fuels. The automotive industry is investing billions of dollars in hydrogen-fueled vehicles—including both internal combustion engines and fuel cells. Major fossil-fuel producers worldwide are investing heavily in hydrogen infrastructure and technology development. The U.S. DOE has committed $1.7 billion to five-year programs in fuel cell vehicles and the infrastructure technologies needed to produce, store, and distribute hydrogen.

Production Efficiency and Cost Challenges

Breakthroughs are needed to bring the cost of hydrogen production down to well below that of current electrolysis technology to ensure the future of the electricity/hydrogen infrastructure. The low-temperature splitting of water by photosynthesis is one possible avenue for breakthrough. Limited research is being done to improve the energy efficiency of water splitting from roughly 10% today to 20% by splitting a water molecule with one photon rather than two.



[1]Nanotubes are tubular carbon fullerene molecules.
[2]Alanates are alkali-metal aluminohydrides that store hydrogen in the crystalline structure of the material.

Source: George Thomas, Ph.D.

FIGURE 3-12. Storage-related R&D efforts must grow and commercialize existing technologies while continuing primary research.

Hydrogen Delivery Infrastructure Challenges

Initial hydrogen delivery will be in both gas and liquid forms, via truck, rail, barge, or on-site generation while the density of use is still low. As in natural gas distribution, pipelines will provide more economical long-distance hydrogen transport when the capital cost is justified by intensity of use. Currently, hydrogen pipelines are used in only a few areas of the U. S., but demonstrate the concept. Air products companies operate short hydrogen pipelines in several states. However, very high-pressure or cryogenic hydrogen pipelines that are greater than 500 miles long will present challenges in materials, construction cost, maintenance, and safe and reliable operation. R&D investment is lacking in these critical areas.

If the hydrogen delivery system were to become an integral part of the electricity generation infrastructure, then the hydrogen pipelines could provide valuable electricity storage. The smart grid concept discussed earlier in this chapter capitalizes on this approach. This system can deliver both hydrogen and electricity over long distances.

Alternate delivery forms are also being developed, such as the transport of hydrogen in safe compounds or chemical forms ranging from solid metal hydrides to ammonia.

Hydrogen Storage Challenges

As with the hydrogen delivery infrastructure, a major obstacle on the road toward hydrogen storage is effectively compressing hydrogen. To achieve an energy density comparable to gasoline, hydrogen must be pressurized at about 10,000 psi. Mechanical compression

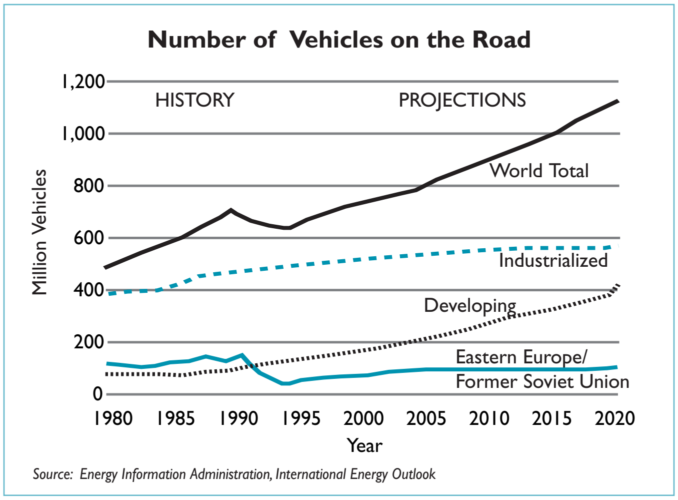


FIGURE 3-13.
Fuel cell applications could significantly mitigate the environmental impacts of the growing use of automobiles.

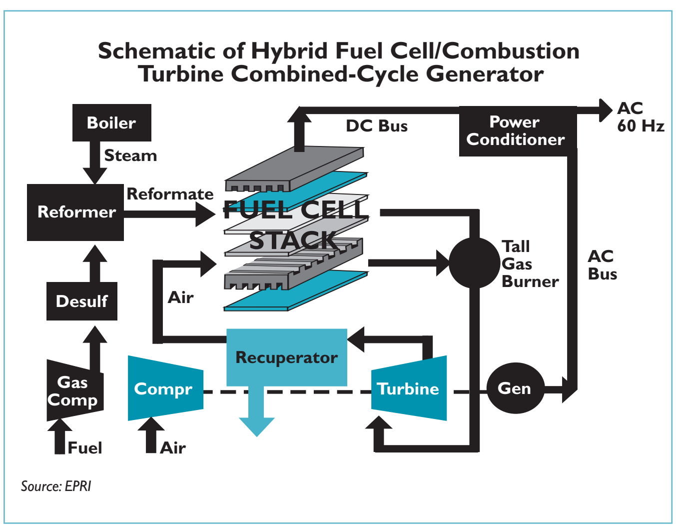


FIGURE 3-14.
Fuel cells for power applications are likely to become more popular over the next decades.

systems are available to reach this very high pressure, but are prohibitively costly and consume about 50% of the energy in the input hydrogen. Studies indicate that hydrogen can also be generated at this density via high-pressure electrolyzers at about 90% efficiency. Such electrolyzers have yet to be built, although programs are underway to develop a high-pressure unit. Promising developments of this nature need far more attention.

High-pressure gas storage tank materials are getting lighter and better able to provide containment, typically using a protective outside layer to improve impact resistance and safety. Hydrogen can also be stored in the delivery pipelines mentioned above by operating the pipeline between high- and low-pressure levels.

Liquid hydrogen stored in cryogenic containers requires less volume than gas storage. However, liquefaction consumes large quantities of electric energy, equivalent to about one third of the energy value of the input hydrogen. The cost of liquid hydrogen containment is also a major concern.

As noted in the previous section, hydrogen can also be stored in a chemical compound using a variety of technologies. In reversible metal-hydride storage, metals are alloyed to optimize both the system weight and the hydrogen recovery temperature. The hydrogen is released from the hydride under certain temperature and pressure conditions. In irreversible storage, the material undergoes a chemical reaction with another substance, such as water, that releases the hydrogen from the hydride. Both of these approaches are in early development.

A further solid-state storage possibility involves the use of carbon nanotubes, but this option is only at the conceptual stage. If successfully developed, it may provide the lightest, smallest, and safest method for small applications, such as vehicles.

Hydrogen Fuel Cell Application Opportunities

Early mass-market hydrogen fuel cells may appear first either in fuel cell electric vehicles or in distributed heat and power applications; the latter is an easier target but investment is focused much more on automotive uses. The Roadmap envisions a global electricity capacity of about 10,000 GW by 2050. By comparison, the world now annually produces about 2,000 GW of power capacity in the form of gasoline engines alone. Thus, about every five years the automotive manufacturing industry produces the equivalent of the world's entire need for electric power capacity in 2050. It may be possible to employ fuel cell vehicles when at rest (typically about 22–23 hours per day) to meet a portion of that grid power need; stationary fuel cells could meet much of the remainder.

Even during a transition period using fossil-derived hydrogen, fuel cells may achieve higher "well-to-wheels" efficiencies and lower total cycle emissions than internal combustion engines and most other conversion devices. Proton exchange membrane (PEM) fuel cells are developing rapidly, and hold great promise for transportation as well as stationary heat and power applications if the technological pace can be accelerated. Far more research is necessary to develop, test feasibility, and deploy practical technology, infrastructure, and high-value applications for fuel cells as well as other direct hydrogen uses.

Applications Challenges

The basic fuel cell limitation is the need for relatively clean and cost-effective hydrogen fuel. Almost all of the hydrogen presently used in industrial applications is formed from natural gas in a process known as steam reforming, which produces hydrogen from methane (CH_4) and generates CO_2 that is currently vented to the atmosphere. Moreover, an energy

Table 3-1. Characteristic Requirements of Fuel Cells for Transportation and Stationary Applications

Characteristic	Transportation	Stationary
Maximum Power	5–100 kW	2 kW–10 MW
Design Life	5,000 hours	50,000 hours
Cost	$50–100/kW	$300–$1,000/kW
Electrical Output	High-voltage AC or DC	48 V DC to 220 V AC
Efficiency	Very high	Very high
Power Range	20 to 1	10 to 1
Power Density (Volume)	Very high	Moderate
Specific Power (Weight)	Very high	Moderate
Operation	Intermittent	Continuous (24/7)
Energy Storage	Possibly	Possibly
Transient Response	1/10th of a second	1/1000th of a second
Short-Term Fuel	Gasoline and diesel	Natural gas/propane
Long-Term Fuel	Hydrogen	Hydrogen

Source: U.S. Department of Energy, EPRI reduction of as much as 30% occurs when natural gas is reformed into hydrogen, and fuel cell power plants presently cost up to 8 times as much to build and cannot be built as large as conventional power plants. If, for the next several generations, steam reformation of natural gas (or other hydrocarbons) remains the only economical way to manufacture hydrogen, an interim solution to manage the CO_2 generated by hydrogen production will be needed.

Outlook for Generation Technologies in the Developing World

One of the key priorities of the Roadmap stakeholders is universal global electrification, ideally with every world inhabitant having minimum access to at least 1,000 kWh/year. The technology to achieve this will require low-cost, clean power generation for rural areas of the developing world that are not connected to a central power grid, as well as modern electricity/hydrogen infrastructure for urban areas.

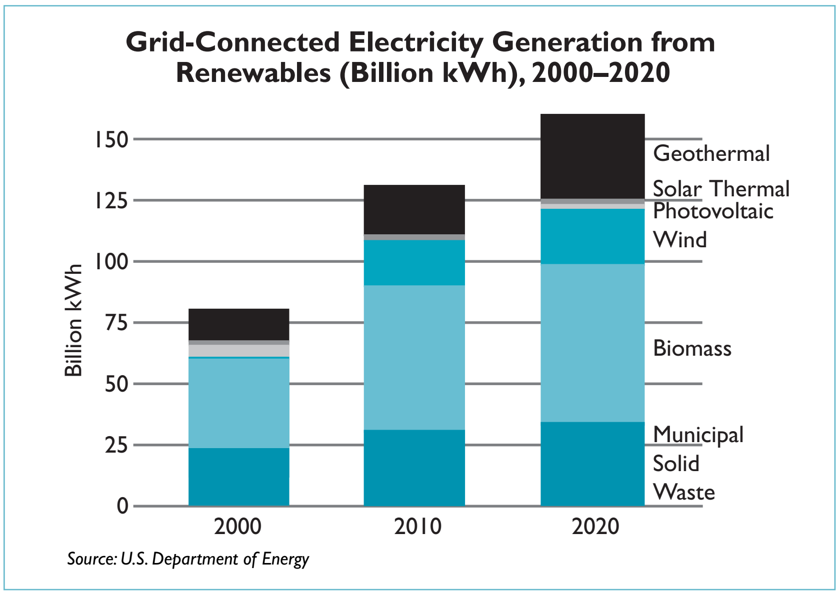


FIGURE 3-15. U.S. generation from non-hydro renewables will double over the next 20 years, and will become an important source of capacity in some parts of the country.

The electrification of the developing world offers the opportunity for a fresh look at designing a 21st century power system. Systems for the developing world are expected to rely on distributed generation for many applications. Distributed designs may be the least costly and quickest way to get power to rural areas in developing countries using readily available indigenous resources. Distributed energy resources will also have a role in supplying the electricity needs of urban areas in developing countries. Note, however, that the markets for power in urban areas of the developing world dwarf the demand in rural areas. This suggests that there will be a role for central station generation in many developing countries that must necessarily rely on indigenous resources to control costs.

The distributed generation portfolio for developing countries is essentially the same as for the developed world. Note that petroleum-based liquid fuels may have an advantage in rural settings, because of the high volumetric energy density and the potential for using existing refineries to refine crude oil into clean fuels.

Renewables will have an especially important role in developing countries. In general, technologies addressing the needs of the developed world can be adapted for use in developing countries. Examples include solar photovoltaics, wind generation, and biomass. To use these technologies effectively in the developing world, technology advances are needed in several areas, such as reducing the capital and operating costs of the equipment, reducing maintenance requirements, and improving the efficiency of end-use technologies. End-use efficiency is particularly important because it can lead to substantial reductions in the power requirements and capital cost of the generation equipment. Work is also needed to develop low-cost storage options—batteries for the most part—to deal with the intermittency problems of wind and solar power.

In many circumstances, power systems in developing countries will be designed to fill the needs of single users. However, village systems will probably require some version of a multiply connected mini-distribution grid, because simple radial distribution schemes will be unable to handle more than one generator on a system.

End-use technologies can also be designed to meet the needs of rural settings. Direct current end-use equipment—lights and power supplies for electronic applications—can be connected directly to DC generators, such as PV systems and fuel cells, without the need for AC inversion of the generator output, and conversion back to DC at the point of use. Other considerations include the need for standardization of voltage levels, interconnection standards, and safety measures such as current limiters. Finally, guidelines for the initial electrification of developing countries can speed the process by summarizing the case histories of other organizations and countries, recognizing that no single solution will suffice for all applications.

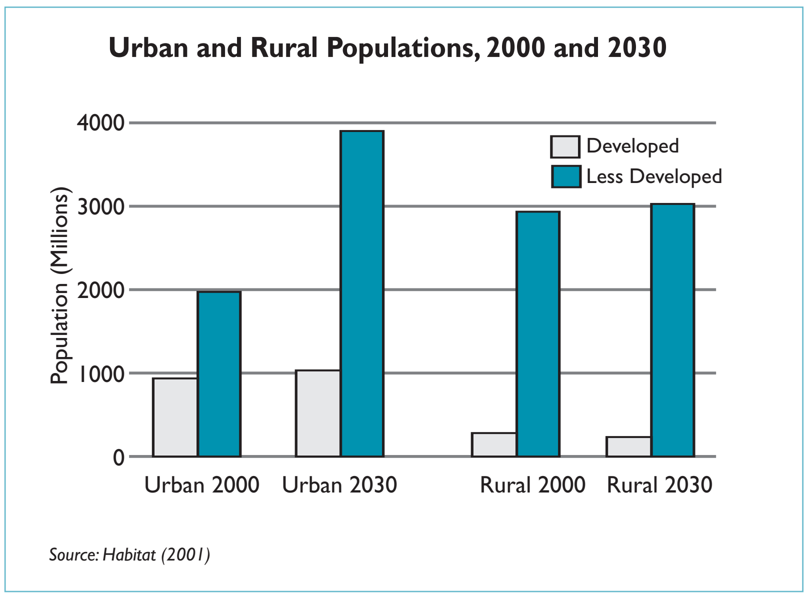


FIGURE 3-16. Electrification efforts must address the needs of fast-growing urban populations.

Electrification of Urban Areas of Developing Countries

In a recent comprehensive survey (2002), the International Energy Agency concluded that access to electric power has increased substantially in the last decade. Currently, it is estimated that about 1.6 billion people do not have any access to electricity, down from 2 billion in the early 1990s. The most dramatic decline in the unserved population has been in China, where incomes rose with the rapid transformation of the Chinese economy—including rural areas hosting township and village enterprises (TVEs) that were among the most vibrant parts of the economy.

However, the demographics of electrification are changing as urban population increases. Today's rural population in developing countries is about 2.8 billion people, while perhaps 1.7 billion live in urban areas. The rural population is expected to remain approximately stable over the next three decades, and population growth in the developing world will concentrate in cities as people move from the countryside. By 2050, the urban population of the less-developed world may double. The pace of this urban shift is one of the many large uncertainties that make projections difficult. Urbanization in the more developed world stands at about 76%; in the less developed world it is only about 40%, so there is enormous potential urban migration in developing countries. The rate of migration may not be entirely independent of electrification; anecdotal evidence suggests that people in rural areas with access to electricity, and the opportunities it provides, experience less pressure to move to cities to find work.

Thus, while rural electrification may stem urban growth, we will still need a technology suite for urban electrification, especially in the case of burgeoning "megacities"—urban population concentrations of 10 million or more. We anticipate that urban electrification will include central station generation solutions, as well as the distributed options discussed above. The central generation technology will focus on fossil fuels (coal, gas, and some oil) in the near term, transitioning to low-carbon technologies (nuclear power, renewables, and sequestration of carbon emitted by fossil fuels). Distributed generation options will be used in the urban context, but their role will differ from that of rural applications. In cities, the high population density will place a premium on space available to support "horizontal" renewables, such as solar energy. Rooftop installations of photovoltaic systems will serve niche applications, but the small rooftop area per capita will limit electricity production. Fossil-fueled distributed generation will also play a role, but emissions of additional air pollution in urban complexes may add to an already heavy burden from automobiles, home heating, and cooking. The emerging drivers for urban electrification in the developing world are thus seen to be broadly similar to the issues in the OECD countries.

Outlook for Technologies to Mitigate Greenhouse Gas Emissions

Addressing potential global climate impacts is becoming an urgent priority for the energy industry and policymakers alike. This reflects the fact that atmospheric CO_2 concentrations have increased 33% over the last 200 years, and are continuing to increase. According to data from insurance giant Munich Re, natural disasters—most of them caused by extreme weather, such as floods, cyclones, or drought—cost more than $81 billion in 2003, up from some $70 billion in damages in 2002. Europe's 2003 heat wave was the biggest single item with $10 billion in agricultural losses alone, while flooding in China cost that country $8 billion. Whether or not this is related to greenhouse gases, it does draw public and political attention to the possibility.

There is no single solution to the climate change conundrum. Activities on all nodes of the electricity value chain—from fuel extraction to power generation to end use—are contributing to the buildup of CO_2 and other greenhouse gases (GHGs) in the atmosphere, with a potential impact on precipitation and other important climactic factors. Addressing today's and tomorrow's complex carbon issues will require a multidisciplinary carbon management strategy consisting of:

- More efficient fossil and non-fossil generation and electricity storage options
- Major expansion of emission-free generation
- More efficient end-use and transportation technologies
- Providing cost-effective generation and end-use technologies to the developing world

- New carbon capture and storage technology
- Advances in utilization of biomass fuels

These technologies are discussed elsewhere in the Roadmap. Here, we focus on the issues surrounding the implementation of a portfolio of technologies that would produce the desired reduction in GHG emissions at a (relatively) low cost.

Table 3-2 illustrates the magnitude of the challenge of reducing GHGs. The table summarizes a variety of carbon management solutions, including low- and zero-carbon power generation technologies and carbon sequestration opportunities, and how each solution could be used to reduce carbon emissions by one gigaton per year (which represents about 15% of current annual CO_2 production). Any one of these technologies would require an extensive infrastructure development effort followed by a costly deployment to even approach the scale of the "one-gigaton" solutions described in the table. For example, the cost of 1,000 advanced coal plants could easily exceed $500 billion, and the costs of other advanced options are not even estimable.

Table 3-2. Different Ways to Save One Gigaton of Carbon Emissions per Year

Technology	One Gigaton Carbon per Year (Billion Tons C per Year)	Major Issues
Near Zero-Emitting Coal Plants	1,000 near zero-emission 500-MW coal units (about 1.6x current U.S. capacity)	Economic Viability, Regulatory Approval, Social Acceptance (sequestration)
Sequestration	3,700 sequestration sites the size of Norway's Sliepner sequestration project (Sliepner is equivalent to a 140-MW gas-fired power plant)	Economic Viability, Regulatory Approval, Social Acceptance
Nuclear	500 new 1,000-MW nuclear plants (about 5x current U.S. capacity)	Economic and Social Viability
Automotive Efficiency	Doubling the efficiency of the U.S. transportation fleet	Point of Diminishing Return Is Reached Without Lifestyle Change
Wind	300x current U.S. capacity	Geographic Limitations, Storage
Solar	6,000x current U.S. solar generation	Economic Viability, Geographic Limitations, Storage
Biomass Fuels from Plantations	Convert a barren area >15 times the size of Iowa's farmland to biomass	Land-Use Changes and Biotech Concerns
Storage in New Forest	Convert a barren area >40 times the size of Iowa's farmland to biomass	Land-Use Changes

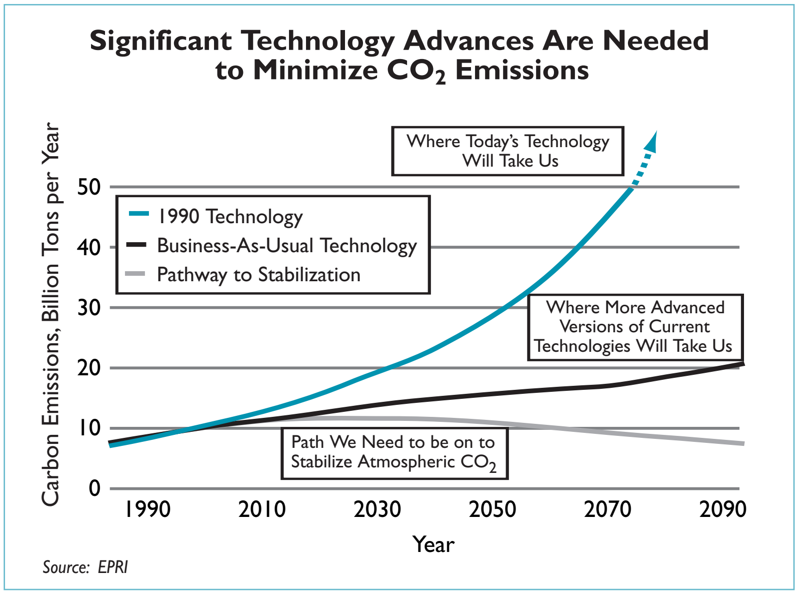


FIGURE 3-17. R&D funding for CO_2 management must increase if we are to address increasingly urgent climate change issues.

The Roadmap recommends a two-step approach to reducing carbon emissions that involves: (1) pursuing a balanced portfolio of generation and carbon removal options, with the goal of reducing costs, and (2) actively seeking novel "game changing" technologies with the potential for high efficiency and the low-cost replacement of the current carbon-based energy system.

Conclusion

Redesigning the global power infrastructure will involve developing flexible and highly efficient generation options, the smart power delivery system, and energy-efficient end-use technologies. At each stage in the process, industry stakeholders will address the economic, environmental, and societal impacts of every business decision. The decision process will become easier as new and better technologies become available, and as better science enables better-informed business and policy decisions. The transformation of the power system will also likely mark the end of the 20th century cost-based commodity business model of the utility industry.

As the commodity orientation disappears, it will be replaced by a series of value-added innovative products and services keyed to consumer needs and expectations. The increase in functionality and consumer control provided by these new products will more than compensate for the higher cost of the underlying commodity. The power system will begin to resemble the telecommunications industry, now dominated by innovations such as mobile wireless phones and computers, phones that double as digital cameras, and phones that incorporate global positioning systems. Power system analogs may include superior power quality, microgrids, rapid outage mitigation, high-efficiency end-use technologies, and various forms of environmentally preferred power options.

The opportunities for technology development to create these new products and services vary widely across the range of industry functions. Generation technologies involve the design, construction, commercialization, and operation of advanced coal, gas, nuclear, and renewable plants. Likewise, building the smart power delivery system will involve architectural design, demonstration, construction, and commercialization. The high cost and financial/technical risk of large power infrastructure projects favor risk sharing among industry and public stakeholders. Collaborative efforts and formation of consortia for technology development and funding will facilitate such projects. The work under way in the Consortium for Electric Infrastructure to Support a Digital Society (CEIDS), for example, addresses the need to start now to develop and deploy the smart power system of the future.

CHAPTER 4 Vision 2025—Enhancing the Value of the Power System

The value of transforming the power delivery infrastructure goes well beyond the opportunities it opens for the U.S. electricity sector. In fact, its greatest value arises from the opportunities it opens for society as a whole. A transformed electricity infrastructure will enable U.S. productivity growth rates to increase substantially, improve energy efficiency and resource utilization, and generate substantial additional wealth to meet the growing environmental requirements of the 21st century, as well as the needs of an aging population. By 2025, a transformed electricity/information infrastructure could, for example, generate as much as $3 trillion dollars a year in additional GDP for the U.S. economy.

Roadmap stakeholders determined that maintaining real wages and quality of life in the face of demographic change will require a sustained increase in productivity over the next several decades. Further, improving the efficiency, reliability, and quality of the power system is one of the key technology investments capable of enabling this needed productivity improvement.

In its current vulnerable state, the U.S. electricity supply system is in need of modernization, not just expansion. Moreover, because many of the technologies necessary for upgrading the power system are in their infancy (or on the drawing board), the process of developing these technologies must begin now. Without a sustained effort to create a new power infrastructure, we will be consigned to a future with an inadequate energy system, and sub-optimal economic growth and societal opportunity.

This chapter describes the productivity challenge that the nation will face in the 21st century as we try to cope with an aging population in the developed world and the urgent need for electrification in the developing world. It describes the current status of the power system and future system requirements, summarizes the payoff to society of implementing the 21st century transformation, and concludes by highlighting opportunities for sustained electricity-enabled improvement in worker productivity in tomorrow's digital society.

Requirements for 2025

Technological change in electricity usage is proceeding very rapidly. In 1980, there were only about two million personal computers in use in the U.S. Although the potential for the PC to improve productivity was anticipated at the time, few foresaw the proliferation of "smart" devices and the demands they place on today's electricity infrastructure. According to Gartner Dataquest, the world's one billionth PC was purchased in April

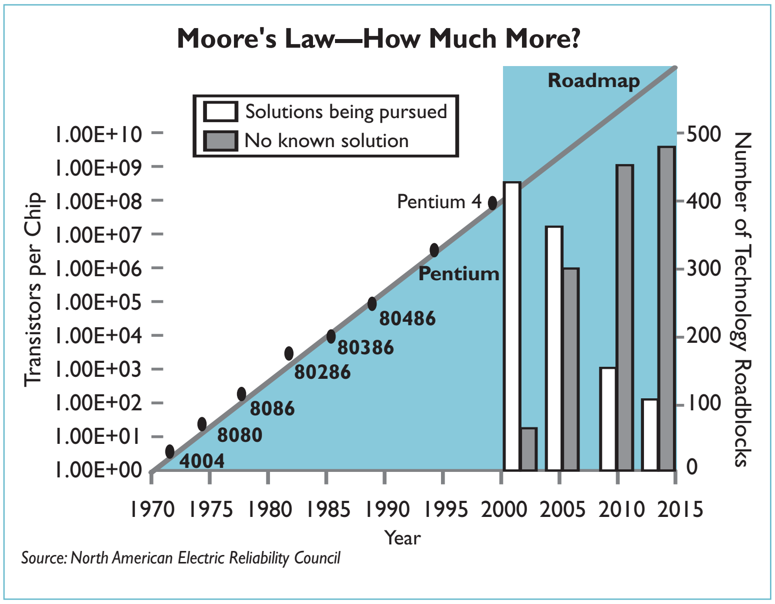


FIGURE 4-1. Massive increases in processing power have been responsible for recent growth in productivity. Significant R&D, as identified in the International Semiconductor Technology Roadmap, is needed to lay the foundation for future leaps in computing capacity.

2002. Moreover, for every microprocessor inside a computer, there are 30 more in stand-alone applications. Moore's Law embodies the growing calculating power and declining cost of these microchips. Continuing this trend toward greater power and speed will require improvements in the chip-making process, which, in turn, will rely in part on improvements in the reliability and quality of the electricity supply.

Similarly, few anticipated the growth of the Internet. Until the recent economic downturn starting in about 2001, traffic on the Internet had been doubling every three months, and is projected to resume rapid growth as the economy recovers. Today, nearly every company and organization in the U.S. has a Web site, and Internet data centers with electric loads of tens to hundreds of megawatts have appeared in most urban centers. The result has been the burgeoning digitization of society, with an attendant rise in the demand for high-reliability, high-quality power to keep all these computers and embedded processors operating smoothly.

Looking ahead toward 2025, some of the key opportunities that will serve to reshape the electricity enterprise include:

- The rise of a universal digital economy with networked microprocessors in everything from household appliances to machine tools, and Internet communications connecting them in real time
- Increased productivity growth at the rate of at least 3% per year in the U.S. economy, afforded by a combination of embedded microprocessor and networked intelligence, and taking advantage of the increased functionality of the smart power grid
- Evolution of competitive electricity markets, marked by the entry of new players at both the wholesale and retail levels, real-time pricing for consumers, and an explosion of commercial transactions
- Expansion of consumer choice, with universal access to lower-cost and lower-emission power, alternative electricity providers, enhanced levels of reliability, and a variety of new energy services
- Proliferation of small electricity generation and storage devices throughout the power system, including at residential locations
- Conversion of increasing public concern for environmental protection into effective emissions reductions and generation efficiency improvements by electricity companies

A common theme uniting these trends is the growing power of the consumer, who must be engaged as a partner rather than as a captive of the electricity supply system. Advances in computing will increasingly serve to distribute intelligence and market power into the hands of the end user. The architecture of the future electricity system, therefore, must accommodate consumers responding to both real-time price signals and a myriad of service options. The change will be sweeping.

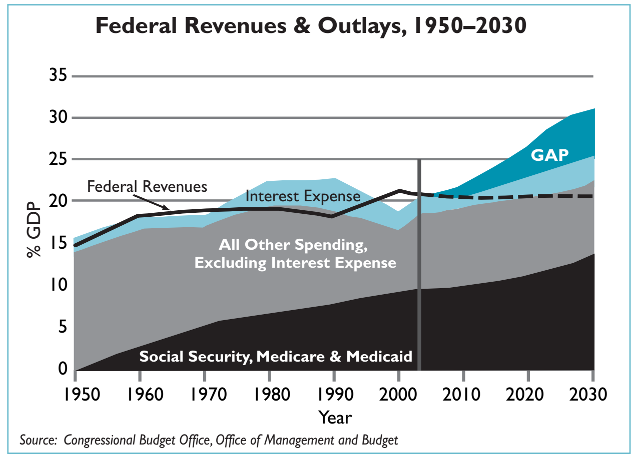


FIGURE 4-2. Without continued growth in productivity, the U.S. federal government will need more funds than ever before to meet the needs of its aging population.

The Productivity Challenge

The continued prosperity and welfare of the nation depends on accelerated economic growth that keeps pace with the demands of the major demographic change underway. Within 30 years, the U.S. dependency ratio (non-working to working population) will increase by 75%. Under business-as-usual projections, this demographic change will require an increase in federal outlays for the human resources portion of the federal budget from 12% of Gross Domestic Product (GDP) to 18%—a percentage equal to the total federal budget today. Even assuming no percentage increases in other budget categories, such as defense, this spending alone would require a 40% increase in taxes and result in a higher fraction of GDP devoted to the federal budget than at any time since the peak of World War II. This underscores the importance of accelerating productivity growth to stimulate economic growth. In constant 2000 dollars, this will mean sustaining a national productivity growth rate of at least 3% per year over this period and beyond (assuming that GDP growth rate equals productivity growth rate plus workforce growth rate). This rate of growth was achieved during the latter half of the 1990s, but it is nearly twice the rate achieved over the period of 1970 to 1995.

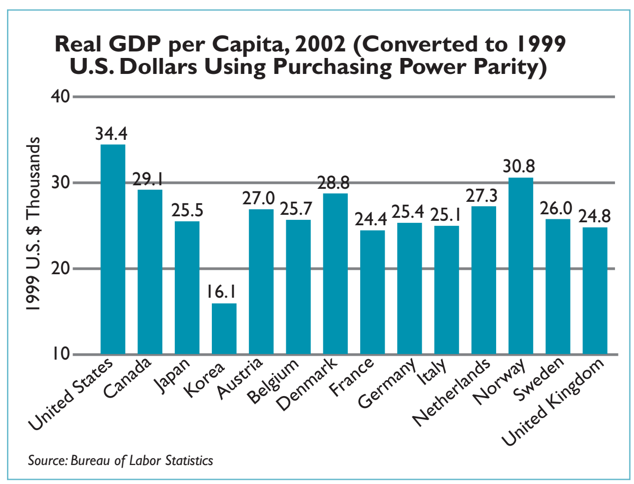


FIGURE 4-3. To remain the world leader in productivity, U.S. companies must develop innovative new applications for IT.

The key to the accelerated productivity growth achieved in the latter half of the last decade appears to have been the rapidly expanding use of digital information and communications technologies (IT). Their advantage is reflected in labor productivity, capital deepening, and total factor productivity (TFP) gains. The productivity advantage achieved through IT is most dramatic in liberalized markets where network improvements in information and communication can significantly enhance operational efficiency, expedite the matching of consumers and suppliers, and more closely align job requirements and worker skills. These advantages are applicable to all markets—product, capital, and labor, and are roughly proportional to the square of the number of network nodes that can be instantaneously linked[1]. The diffusion of these IT advantages is, however, still in its infancy relative to the fraction of the potential markets engaged. This suggests that the economy has only scratched the surface in terms of exploiting the longer-run productivity gains that are likely to result from the creative use of digital IT.

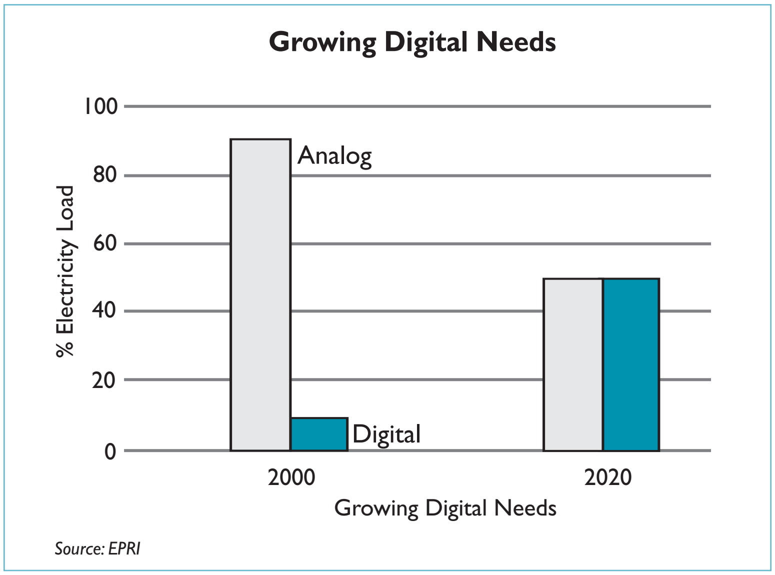


FIGURE 4-4. As the economy depends more and more on digital devices, demand for high-quality power will grow.

Dale Jorgenson and others note that knowledge workers are using computers not just to do old tasks more quickly, but also to perform unique and previously unimagined functions[2]. Given this recent experience, it is important to assess whether these high productivity levels are sustainable. It's also important to recognize that high power quality and reliability are emerging as critically important adjuncts to sustaining the chip and information technology industries.

The 1% loss in GDP currently ascribed to power disruptions described later in this chapter offers a near-term incentive to improve productivity. Success in developing and deploying the technology of an enhanced electricity infrastructure could conceivably support sustained GDP growth of 4% per year (as compared to the 3.5% projection by the Energy Information Administration) by removing the losses from power disruptions, as well as lifting the brake on future growth of the digital economy[3]. In particular, the two-way flow of communication and power through an "energy/information portal" would allow faster and deeper penetration of productivity-enhancing digital technology in all sectors of the economy.

Infrastructure Implications

Despite the promise of digital technology for boosting U.S. productivity growth rates, it remains a "thoroughbred technology," given its speed and fragility. It is highly sensitive to even the slightest disruption in power (an outage of much less than a single cycle can shut down a digitally controlled industrial process and lead to idled workers, loss of product, and equipment damage). Commercial and industrial processes are also vulnerable to variations in power quality due to transients, harmonics, and voltage sags. "Digital quality power," with sufficient reliability and quality to serve these growing digital loads, now represents less than 10% of total electrical load in the U.S. It is expected to reach 30% by 2020 under

[1]Kevin Kelly, *New Rules for the New Economy,* Penguin Books, 1998.
[2]Dale Jorgenson, "Economic Growth in the Information Age," October 12, 2002.
[3]*Annual Energy Outlook 2004 with Projections to 2025*, U.S. Department of Energy, DOE/EIA-0383, January 2004.

business-as-usual conditions, and as much as 50% under optimum conditions where the power system is revitalized with new all-electronic controls. (See Figure 4-4.)

Recent data suggest that productivity improvements and better quality products made with new, high-tech manufacturing processes have added as much as $1 trillion to the U.S. economy over the last five years[4]. These gains are due in part to the value that digital control of the manufacturing processes delivers by enabling improved productivity, labor cost savings, and flat pricing of durable goods. The sophistication of information technology applications in manufacturing is growing. The continuation of this trend, combined with the higher reliability for electricity demanded by these technologies, makes a compelling case for research, development, and demonstration of technologies to improve the security, quality, reliability, and availability (SQRA) of the power system.

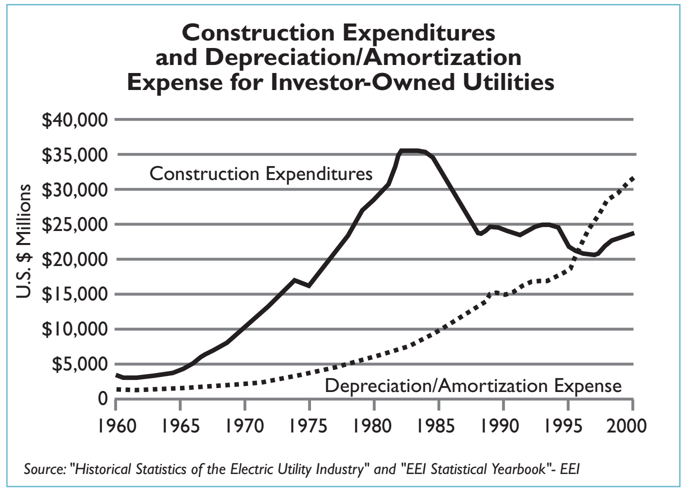


FIGURE 4-5. Greater investment in generation assets is needed to ensure continued system performance.

In contrast, the electricity supply infrastructure has changed very little, and is making almost no provision to meet the needs of the digital economy. In fact, infrastructure investment has reached new lows. Capital expenditures by U.S. electricity providers were only about 12% of revenues during the 1990s, less than one half of historic minimum levels, and even below the level reached only briefly during the Depression. In particular, the delivery system is not keeping up with the demands of digital technology. The transmission and distribution systems were designed for the industrial era of the 1950s and 1960s, when mechanical switching and radial network design were adequate. Annual investment in the transmission system has been cut in half since 1975. Despite increased demands placed on the system, capital expenditure plans announced by utility companies suggest that the under-funding trend is continuing.

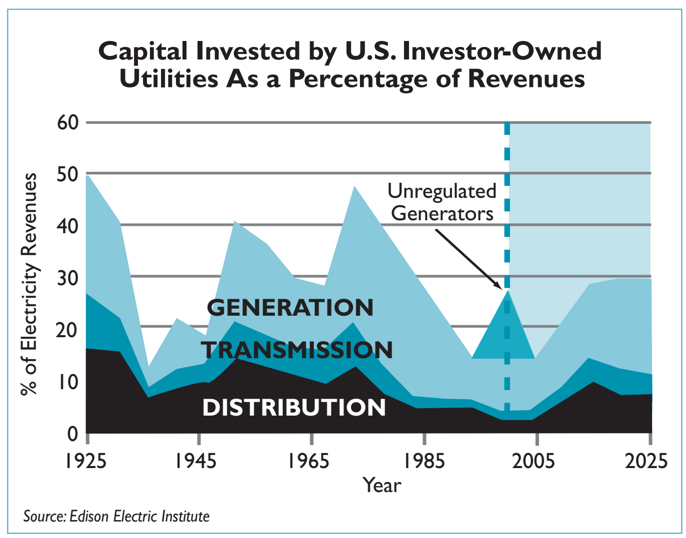


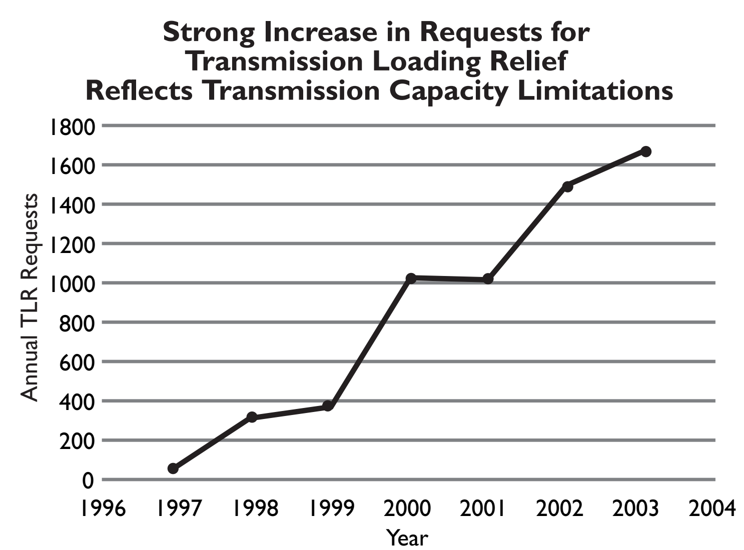
FIGURE 4-6. Capital investment must increase to ensure the availability of a fully integrated "smart" power system capable of adding economic value.

On the generation side of the equation (as shown in Figure 4-5), depreciation expenses have exceeded construction expenses in recent years. Since depreciation is the process by which a company gradually records the loss in value of fixed assets, the chart shows that the industry is now generally in a "harvest the assets" mode rather than an "invest in the future of the business" mode. An exception is the "blip" in capital expenditure resulting from investment in

[4] "Producing Prosperity—Manufacturing Technology's Unmeasured Role in Economic Expansion," The Association for Manufacturing Technology, 2000.

unregulated generating plants over the past few years. This trend has reversed itself since reaching a peak in 2001 as plants were rushed into operation to respond to the opening of the wholesale power market.

Since that time, the downturn in the economy has led many generating companies to postpone or cancel new plant orders, and the industry now faces an oversupply of generation capacity. This boom/bust pattern may continue to plague future generating planning efforts in the absence of an integrated approach to power system management. One concern is that a large gap may open between the economy and the infrastructure that supports it. Without substantial investment, the electricity supply system will almost certainly become a drag on future U.S. productivity growth rates. Figure 4-6 shows the decline in capital investment following the peak in the early 1970s leading up to the unregulated generation investment blip. Except for this blip, investments as a percentage of revenues have declined continuously since 1970. The extension of the graph to 2025 is an assessment of the increased investment rate needed to rebuild and modernize the power system.



Source: North American Electric Reliability Council

FIGURE 4-7. Today's transmission infrastructure must be overhauled to meet tomorrow's power needs.

Signposts of Trouble

There are already signposts of trouble. The power supply system is growing increasingly vulnerable. In some parts of the country, electricity consumers already suffer from inadequate generation, poor power quality, or transmission congestion during periods of high demand. This process is often exacerbated by the historically low patterns of investment in infrastructure. Power interferences and disturbances can sometimes lead to economic impacts that cascade through the value chain, leading to losses sustained by industrial customers and their suppliers alike. Although the losses to consumers are large and varied, there have been very little data to document and quantify the current situation comprehensively. Most traditional estimates begin and end with the momentary impact at the point of disturbance.

However, more accurate estimates indicate that the losses go well beyond the immediate point of impact. For example, a nearly imperceptible one-second sag in voltage in one of the microprocessors running a paint gun in an auto plant could destroy the finish on one or more cars, and disrupt part of the assembly process. Similarly, a momentary disturbance at a semiconductor-fabrication plant producing microprocessors could ruin an entire 30-hour batch, and possibly the equipment itself.

Further, in the tightly integrated supply lines typical of today's just-in-time production, a small disruption can cascade both upstream and downstream to hundreds of local suppliers, compounding the economic loss. In general, economic loss can include downtime, loss of raw material, damaged product, damaged equipment, disruption of supply chains, and even bankruptcy. In a few industries, such as information technology and financial services, the concerns over power reliability have now become "bet-the-company" investment decisions. At one new financial data center in Connecticut, for example, the cost of power conditioning accounted for nearly two thirds of the cost of the entire facility. A similar ratio of power conditioning to total facility cost (68%) was found at a new Internet facility in Miami. These are anecdotal figures, but they do point to the fact that the need for, and value of, high-quality electric power has risen dramatically in the last few years.

To better understand the economic loss from power reliability and power quality problems of all types, EPRI extensively surveyed some key industries in 2000 and extrapolated the results (see the sidebar on "Estimating the Costs of Power Disturbances"). The survey results showed that outage costs were substantially higher than historic estimates, and the subsequent analyses indicated that the aggregate economic loss to the nation has climbed to more than $100 billion per year, or more than 1% of U.S. GDP. These results certainly warrant further confirmation, but they are not out of line with the literally total reliance of business, industry, and commerce on electricity, and the demands of the rapidly expanding digital revolution.

The costs of these power disturbances are parasitic in nature, and go largely unreported. They are passed on by businesses of all types to consumers in the cost of goods and services. Such costs are almost certain to climb in the years ahead unless action is taken to improve power reliability and quality.

There are other troubling signs of problems with the current power infrastructure. Serious incidents reflecting constrained capacity, often accompanied by price spiking and questionable financial dealings, have occurred in seven of the last eight years. These problems have affected the Midwest, California, and, most recently, the Northeast. Most observers conclude that the problems experienced during the last two years would have been even worse had it not been for the economic downturn and resulting drop in electricity demand.

Other problems arise from the threat of terrorist acts and sabotage that would compromise the security of the power system. The electricity system is a large and inviting target, and disruption of the grid would cause loss of human life and losses to society and the economy that extend far beyond the power system itself.

A final area of grid vulnerability is its growing inability to support the needs of competitive markets for electricity and related products and services. A massive transformation is needed to provide the grid with the policies, protocols, and technologies needed to support markets.

Estimating the Costs of Power Disturbances

Data on the economic impact of power outages and disturbances are difficult to obtain. In nearly all cases, costs are passed on to the customer, who neither sees them nor understands their impact. To obtain more reliable information on these costs, EPRI conducted a survey of 985 firms in three sectors of the economy with high sensitivity to power reliability. The firms surveyed were in the digital economy sector (data storage, financial and online services, etc.), the continuous process manufacturing sector, and the fabrication and essential services sector. The detailed survey asked respondents to estimate their costs arising from a series of power-quality and reliability events, based upon their recent experience. Data were collected and analyzed using the methods described below.

The estimated annual losses totaled $52 billion for the three sectors surveyed. Out of a total of 12 million business establishments in the U.S., about 2 million, or 17%, are represented by these three sectors. The average loss per business was estimated at $26,700 per year. Next, the researchers estimated the losses for sectors that they did not survey. They used two bounding assumptions to reflect the fact that the non-surveyed businesses would have a lower sensitivity to power outages than the surveyed sectors. In the first case, they assumed that the non-surveyed establishments suffered half the loss of the surveyed establishments. In numerical terms, the resulting average loss per establishment was $13,350/year for each of 10 million firms. In this case, the total economic loss was estimated at $133.5 billion for the non-surveyed firms, plus $52 billion for the surveyed businesses, for a total of $186 billion. In the second case, the loss per establishment for non-surveyed companies was assumed to be one quarter of the loss for surveyed companies. This leads to an estimated total economic loss of $120 billion.

Alternative approaches were also used to estimate losses for non-surveyed firms by looking at average revenues. This method assumes that the larger companies in the three surveyed sectors would experience greater losses than smaller companies (on average) in the non-surveyed sectors. The three sectors surveyed constitute about 40% of GDP, or $4 trillion per year (U.S. GDP is approximately $10 trillion per year). Since there are 2 million such establishments, the average revenue per company is about $2 million per year. With economic losses estimated at $26,700 per company, losses in the surveyed sector equal roughly 1.3% of revenues. For the establishments not surveyed, the share of GDP is 60%. So the average revenue per company is $6 trillion divided by 10 million companies = $600,000 per company. For the case in which the losses at the non-surveyed companies are assumed to be one quarter of the losses at the surveyed companies, the loss per company is $6,700, divided by the average revenue of $600,000, or 1.1% of revenue. The loss estimates are again in the range of 1% of GDP, or $100 billion per year.

Finally, the researchers estimated the effect of scaling the losses by the GDP contribution of the sectors. This is what several reviewers of this analysis had suggested. In this case, the losses are $72 billion if the sensitivity of non-surveyed establishments is one quarter of surveyed establishments and $91 billion if the sensitivity is one half. All of the analytical methods and

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assumptions lead to economic losses that are in the ballpark of $100 billion per year, validating the thesis that the losses due to U.S. power system disturbances are much higher than expected, and have become the source of a significant loss to the U.S. economy. The loss represents an additional cost of about 50 cents for every dollar spent for electricity.

Technologies are now available that can reduce the frequency of disturbances and the damage they cause. Implementing these technologies over the next two decades should conservatively reduce outage costs by 50% to 80%. However, failure to take action will result in further degradation of power system reliability, leading to an increase in costs, perhaps by as much as an additional $200 billion per year over a ten-year period.

In addition to the direct costs of disturbances, some high-technology and information-based companies need essentially "perfect power." Increasingly, these companies are installing on-site equipment to meet their specialized needs. In a growing number of cases, the cost of installing power conditioning equipment in buildings has begun to dominate the cost of construction. So far, only anecdotal data are available to support this apparent trend. However, it's important to note that these preventive costs are not included in the estimated costs of disturbances.

The uncertainty associated with these analyses is high, and better data and synthesis are needed to quantify the value of a transformed power sector. Therefore, EPRI is encouraging further research into the cost of power outages. Comprehensive assessments will require that researchers go into the field to get closer to the reality of how the costs of power disturbances emanate from the source. Refined estimates of the source and magnitude of power system losses will prove valuable as a means of determining how best to improve power system reliability and quality.

Short-Term and Long-Term Responses

Responses to the growing need for improved power quality are both short term and long term. Many of the short-term responses lie on the consumer's side of the meter, where businesses with the need for "perfect power," such as financial institutions and high-tech manufacturing, will be able to gain higher levels of reliability through the use of redundant power supply and power conditioning systems. The demand for uninterruptible power supplies on or close to the consumer premises is growing rapidly, and some high-tech firms and industrial parks have begun to plan for their own microgrids—small islands of digital quality power in a sea of traditional power.

Some short-term solutions, however, are upstream of the meter. Activities such as improving maintenance practices, monitoring the "health" of critical equipment, and better preparations for outage recovery can materially reduce productivity losses. One reason that these and other fixes have not been implemented on a wide scale is the mismatch between who gains and who pays—in this case the electricity end user realizes the benefits, while the distribution company incurs the costs through increasingly uncertain returns on investment and rate freezes. Moreover, the costs of unreliability are usually internalized by the commercial end user, who passes the costs on to its consumers—a mechanism typically not available to the distribution companies. Some industry stakeholders believe that, as awareness of the problem and the potential investment benefits grows, cost recovery will be more certain.

In the longer term, it is crucial that the supporting power supply infrastructure be able to keep pace with the growing digitization of the economy. The rigor and pace of global competition now impacting virtually every business in the U.S. are major drivers in the move to digitally controlled electricity use. It is hard to imagine any major industrial process, manufacturing facility, or commercial business in 2020 that would not be fully utilizing digital control with interactive links to its consumers through the "energy web." As described in *Wired* (July 2001), the energy web will become a national system in which "every node in the power network is awake, responsive, adaptive, price-smart, eco-sensitive, real-time, flexible, and interconnected with everything else."

Vision of a More Productive U.S. Electricity System

Table 4-1 summarizes two potential futures for the power system in the year 2025. The Enhanced Productivity Case (right-hand column) illustrates the potential gains enabled in part by the transformation of the electricity infrastructure. It reflects analysis performed by EPRI and other organizations, including recently published reports by the Energy Future Coalition (Challenge and Opportunity: Creating a New Energy Future) and EPRI (Electricity Sector Framework for the Future: Achieving the 21st Century Transformation). The Enhanced Productivity Case is compared with a Reference Case derived mostly from the projections of the U.S. DOE Energy Information Administration[5]. Relative to the Reference Case, the Enhanced Productivity Case shows improvements in the electricity intensity of economic activity, supply and end-use efficiencies, reduced CO_2 emissions, and the performance of the energy delivery system.

It is important to note that the Enhanced Productivity Case is not a forecast in the traditional sense. Instead, this scenario is a set of challenging yet achievable "stretch goals" made possible by an enhanced electricity infrastructure. They reflect the opportunities afforded by accelerating the fundamental technological changes underway in the U.S. economy and the power system. Achieving these goals will require breakthroughs in a sweeping set of electricity technologies as outlined in Chapter 3. These technologies will improve the functionality of the power system for both grid and off-grid applications.

[5] *Annual Energy Outlook 2004 with Projections to 2025*, U.S. Department of Energy, DOE/EIA-0383 January 2004.

Table 4-1. Potential Benefits of the Enhanced Productivity Case				
	2002	2025		
	Baseline[6]	Reference Case	Enhanced Productivity Case	Improvement of Enhanced Productivity Over Reference Case
Demand Characteristics				
Electricity Consumption (Billion kWh)	3,800	5,800	4,900–5,200[7]	10–15% reduction
Delivered Electricity Intensity (kWh/$GDP)	0.40	0.28	0.20	29% reduction
% Demand Reduction Response at Peak	6%	15%	25%	66% increase
% Load Requiring Digital Quality Power	<10%	30%	50%	66% increase
Generation				
% Distributed Generation (<20 MW/Unit)	7%	15%	25%	70% increase
Installed Capacity (Gigawatts)	820	1200	1000	17% reduction
Carbon Dioxide Emissions from Electricity Generation (Million Metric Tons of C)	607	900	720	20% reduction
Transmission				
Miles of Lines >230 kV	156,000	200,000	180,000	10% reduction
Transmission Density (MW/Mile)	4.84	4.6	5.6	22% increase
Transmission Reliability	4-nines	<4-nines	5-nines	NA
Economic Growth				
Productivity Growth Rate (%/Year)	2.9[8]	2.5	3.2	28% increase
GDP Growth Rate[9] (%/Year)	4.2	3.5	4.2	20% increase
Real GDP ($ Billion 1996)	9,400	20,700	24,300	17% increase
Cost of Power Disturbances to Businesses ($ Billion 1996)	100	200	20	90% reduction

[6]The baseline specifications are primarily based on DOE/EIA projections and largely represent extrapolations of current trends.
[7]Assumes an average capacity factor of 57%, including DER.
[8]Based on average annual productivity growth, 1995–2000. Labor input is 1.3%. (Data from Jorgenson)
[9]Labor input is assumed to be 1.0% for both the Reference Case and the Enhanced Productivity Case.

The Productivity Payoff

The value of the productivity transformation, summarized in Table 4-1, derives from several specific elements. First, the growth in electricity consumption is lower in the Enhanced Productivity Case (1.1% per year versus 1.9% in the Reference Case) and the electricity intensity is 30% lower. These improvements suggest that energy efficiency is increasing as well as worker efficiency. Moreover, these efficiencies have the potential for reducing carbon dioxide emissions by 20%.

The transformed power system described in Chapter 3 will also provide the basis for greater efficiency and productivity. A smart grid coupled to an automated distribution system can reduce the requirement for added transmission capacity from 44,000 miles of line greater than 230 kW to 24,000 miles. Transmission density will also increase through better utilization of existing equipment and right-of-way. These improvements are achievable because of the prospect for increasing distributed energy resources. Increasing DER will reduce the requirement for central generation additions, and it can improve reliability and reduce transmission congestion.

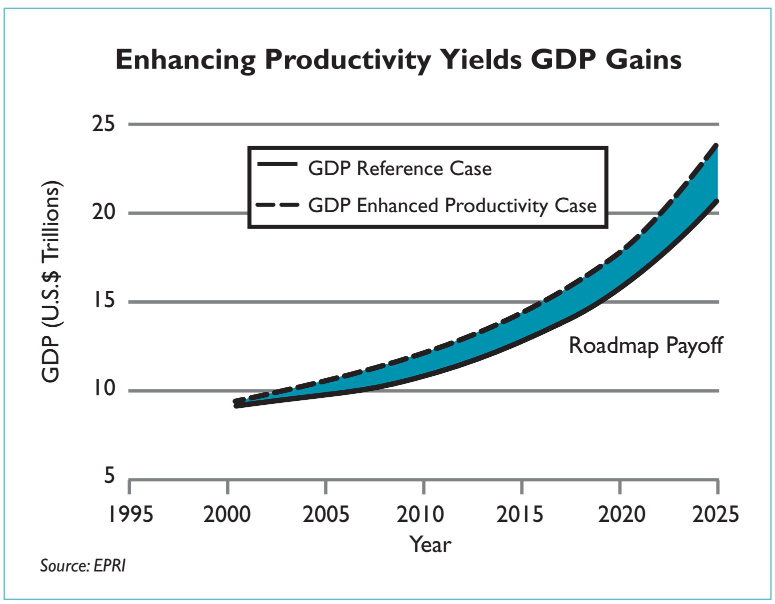


FIGURE 4-8. Under the Roadmap scenario, productivity growth increases while environmental costs decrease.

These are much more ambitious goals for economic savings from electricity usage than are typically forecasted or advocated today. However, similar instances of sharp reductions in energy intensity have occurred in the past both for total energy and for electricity. U.S. energy intensity declined by this same fraction from 1973 to 1999. In addition, since the oil embargo of 1973, the U.S. has gained nearly three times the energy from efficiency savings as it has from the net expansion of all domestic supplies combined. Moreover, the electricity intensity targets of the Enhanced Productivity Case would allow the U.S. to achieve the energy efficiency levels of Japan and Germany, which have the lowest electricity intensities in the developed world.

Figure 4-8 summarizes the **economic payoff** of rapidly developing and deploying the technology of the "21st Century Transformation" (described in the EPRI report Electricity Sector Framework for the Future, available at epri.com), one that is fully capable of supporting the demands of the digital society and economy. In this enhanced scenario, productivity growth rates are higher and the economy expands more rapidly, while energy intensity and carbon emissions are substantially reduced.

In the Enhanced Productivity Case, the GDP growth rate is sustained at 4.2% per annum, consistent with the level attained during the economic boom of the latter half of the 1990s. The higher GDP growth rate will be sustainable in the future if there is continued growth in worker productivity, enabled by the highly reliable digital power infrastructure. The transformed power system will help workers perform existing and completely new functions quickly, accurately, and efficiently. When corrected for workforce growth, productivity in the Enhanced Productivity Case will increase by 3.2% per year. In this sense, transformed power reliability and quality become enabling agents—they are necessary for unleashing and streamlining the digital economy. The payoff from this economic progress is the potential for creating about **$3 trillion per year** in additional GDP that would be available to both the private and public sectors by 2025.

An additional critical issue is the security of the power system. It is clear that national security would benefit from the improved electricity infrastructure envisioned in the 21st century transformation. A more reliable, smart, adaptive, and efficient electricity system that is better able to meet the demands of a digital economy would certainly contribute to national energy system security. Given the essential nature of electricity service to the nation's economy and welfare, any significant interruption could be disastrous. While infrastructure security is critically important, its value is not readily quantifiable. Uncertainties surrounding the business model for enhancing security (public sector financing versus market-based approaches, for example) further contribute to the difficulties in enabling security improvements today.

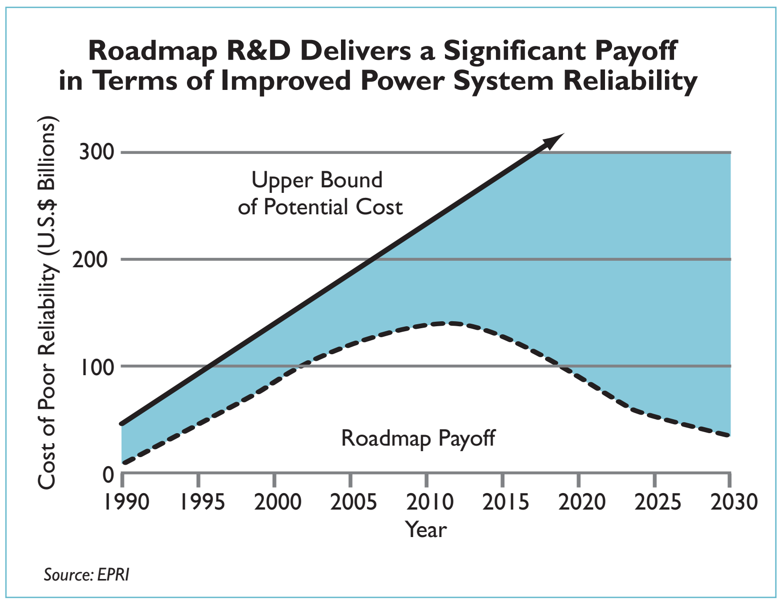


FIGURE 4-9. The Roadmap delivers a significant payoff in terms of reducing the economic loss from power disturbances.

The Reliability Payoff

The current annual domestic reliability loss of approximately $100 billion (see sidebar "Estimating the Costs of Power Disturbances") may be only the start of a longer-term trend. Figure 4-9 shows that in a worst-case scenario, losses could reach as much as $300 billion per year by 2015. (The "worst case" assumes the cost of poor reliability will grow in proportion to annual growth in electricity consumption.) In reality, there is considerable uncertainty regarding future reliability losses, but it's clear that these losses will be linked to the growth in high power quality applications anticipated in the 21st century. The lower Roadmap payoff curve shows the cost reduction achievable by eliminating roughly 80% of the current reliability losses. The reduction in losses is enabled by large-sale implementation of the self-healing power system. (See Chapter 3 for a description of the technology elements of the self-healing grid.) As Figure 4-9 indicates, the benefits of a modern power infrastructure will be phased in over the next 25 years as the new technology elements are introduced. The shaded area indicates the total benefit of improving reliability.

Figure 4-9 also suggests that the improvement in reliability over the next 10 years may be as much as $10 billion per year as the industry implements current off-the-shelf solutions. The rate of increase in reliability may be smaller in the out years because further improvements will require technology advancements not yet in hand.

Implementing initiatives to improve reliability will require an improved understanding among all industry stakeholders on critical issues such as who will gain from and pay for an improved power infrastructure, how to create incentives for making the necessary investments, and how to manage and reduce the risk of investing in the power system. As noted above, there are currently some questions surrounding these and other reliability issues. The Roadmap can help prioritize the issues, and highlight the large benefit to cost ratio of improving reliability.

Conclusion

Electricity has had a long history of stimulating and sustaining economic growth and improving the efficiencies of all factors of production. This is particularly true for the productivity of labor and energy. Now, the smart grid and the energy/information portal will drive a new wave of productivity growth. Combined with the development of advanced end-use electrotechnologies, the 21st century transformation of the electricity sector will introduce new efficiencies into the use of energy, labor, and capital for industry, business, and homes.

Improving worker productivity is particularly important as we look toward the demographic challenges of the new century. Although the effects of declining birthrates combined with aging populations are currently less pronounced in developed countries with large immigrant populations—such as the U.S., Canada, and Australia—the growing societal needs of an aging population will ultimately affect all countries, developed and developing. Worker productivity will have to increase substantially to meet the social costs of a growing retired population.

The vision of the 21st century transformation will be critically important to boosting productivity growth rates, and enabling trillions of dollars per year of additional revenue for use by both the private and public sectors. Most industry stakeholders have found the potential payoff of this vision sufficiently compelling to warrant concerted public/private collaboration and commitment to make it happen.

CHAPTER 5

Vision 2050—Universal Global Electrification

> The developed world has reached a critical point at which its future economic, environmental, and social health depends upon increasing the rest of the world's access to clean, cost-effective energy. This is the crux of the sustainability challenge of the 21st century. Improving access to electricity must play a central role in managing sustainable growth because:
>
> - Electricity allows for diversity in primary energy supply, yet is an intrinsically clean energy carrier.
> - Electric services enable the modern technological innovation essential to human opportunity.

The 250 years from 1800 to 2050 will be remembered as a period of intense technological expansion that fundamentally increased humankind's ability to harness energy. The technological advances of this era will have enabled modern economies to flourish and the human population to grow rapidly. In fact, over this period, human population will have increased tenfold, from less than one billion to about 9 billion. (See Figure 5-1.) However, as of today, the world has not yet reached an equilibrium point in terms of population, energy, or environment that can be called "sustainable." About one quarter of the human race lives today without access to modern energy services, such as electricity. This energy gap tends to be greatest in those regions where population is growing most rapidly—the very regions where improved access to modern energy services would offer the greatest benefits. This chapter considers options for improving access to affordable and reliable electricity while protecting environmental resources for future generations.

Defining Sustainability

Because the term "sustainability" is often abused, it needs clarification to serve as an overarching global goal. The United Nations Commission on Environment and Development, the so-called "Bruntland Commission," first brought the sustainability issue to the world stage in 1987. 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. In the context of the Roadmap, a somewhat stronger formulation seems more appropriate. For our purposes, sustainability refers to **the balancing of human activity with the earth's resources** such that the opportunity for maximum well-being can be maintained universally and indefinitely. Throughout history, the essential balancing agent at any given time has been the science and technology used to extract and harness energy from nature. Therefore, this Roadmap focuses on science and technology, and this chapter examines how to ensure that all the world's population—the expected 9 billion in 2050—can reap the benefits of opportunity that are essential to achieving true global sustainability.

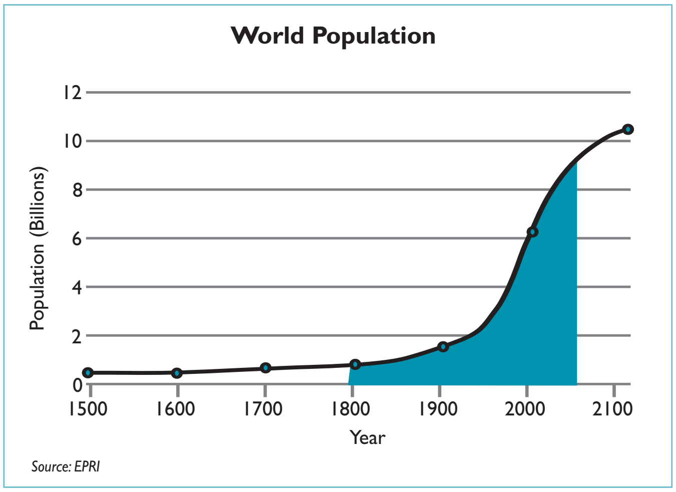


FIGURE 5-1. Electrification is critical to meeting the needs of a rapidly growing world population.

Connecting Energy, Population, and the Modern Economy

Prior to the advent of agriculture, the human population of the world had stabilized at a level of about 10 million, constrained by the total per capita energy available from biomass of less than 3,000 Calories (13 megajoules) per day. About 10,000 years ago, the Agrarian Revolution harnessed biomass and animal power to raise per capita energy consumption needed for the emergence of cities and civilization to about 10,000 Calories (42 megajoules) per day, which, in turn, enabled the global human population to approach one billion by the end of this era. The resulting population of Western Europe ultimately reached 40–60 persons per km^2, a density about 100 times greater than that of the Neolithic hunter-gatherers.

With the onset of the Industrial Revolution, humankind's ability to extract and use energy from nature once again dramatically increased. Whereas biomass and animal power fueled the agrarian boom, fossil fuels powered the Industrial Revolution and the modern societies that grew out of it. Their widespread availability allowed the human population to expand by an order of magnitude—an expansion that continues today—with impacts on nature and on societies worldwide still unfolding.

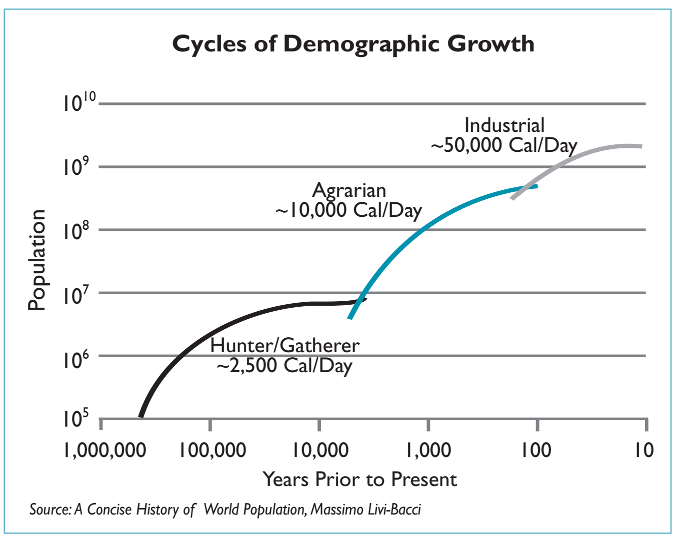


FIGURE 5-2. Bringing the world's population into the industrial age is a significant challenge for the 21st century.

The emergence of a modern society currently requires at least 50,000 Calories (210 megajoules) of primary energy per capita per day. (See Figure 5-2.) Although the advanced industrial economies already operate at much higher levels—typically about 100,000 Calories (420 megajoules) per person—the rest of the world is still typically at lower levels of energy access, often at the levels of earlier agrarian economies. This produces an unsustainable mismatch between energy access and population density.

Improving Efficiency Along the Energy Supply Chain

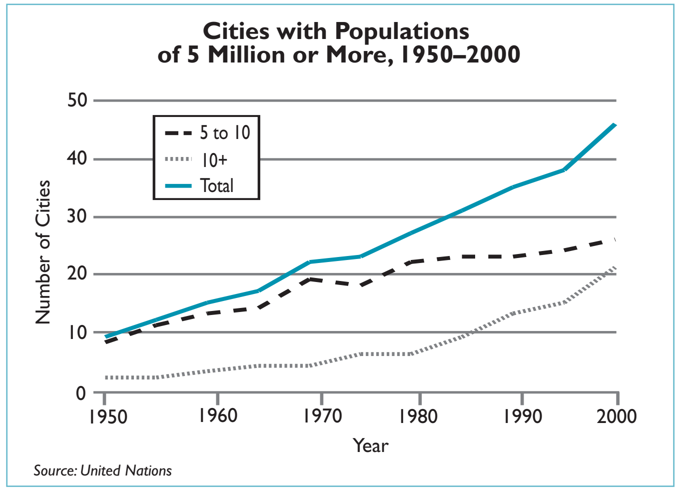


FIGURE 5-3. The availability of electricity has been a major driver of urbanization.

As societies strive to improve access to modern energy services, they must also find ways to make the energy system more efficient. The efficiency of the full energy supply chain (extraction, conversion, delivery, and consumption) has only reached about 5%; therefore, large opportunities for improving efficiency remain at every stage in this chain. For example, using today's energy sources and technology, achieving universal supply of at least 50,000 Calories (210 megajoules) per day per capita by 2050 would approximately triple the current global rate of energy consumption. Fortunately, realizing technological advancements that are now visible throughout the energy supply chain could reduce the 50,000 Calories (210 megajoules) per day threshold by 2050 to as little as 30,000 Calories (125 megajoules) per day with no loss in economic productivity or quality of life potential. The efficiency of electricity generation, for example, now typically in the 30% range, could easily reach, on average, 50–60% by 2050. Further, the emergence of low wattage lighting and appliances aimed at the developing world suggests rapid technological progress in household energy efficiency. Even the automobile is on the threshold of transformative change.

Electrifying the World

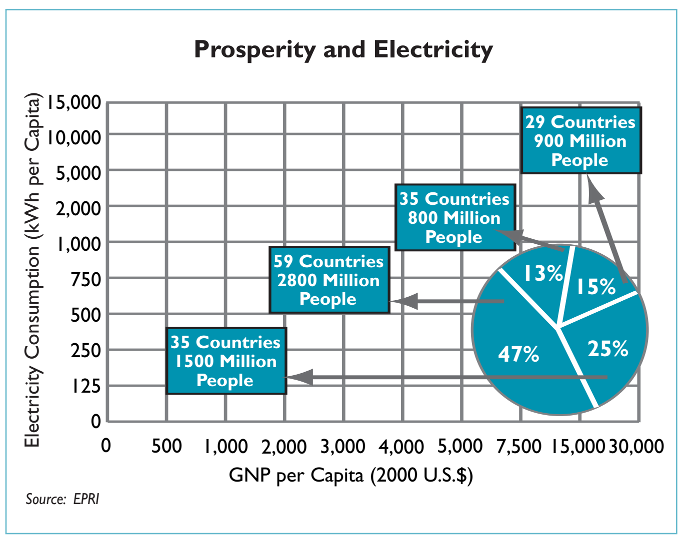


FIGURE 5-4. Prosperity is closely correlated with electrification.

As a practical matter, electricity must form the backbone for the transition to a globally sustainable energy system and the modernization process it enables. Electricity's ability to transform the broad array of raw energy and other natural resources efficiently and precisely into useful goods and services, irrespective of scale, distinguishes it from all other energy forms. Electricity also serves as the unique energy prime mover enabling technical innovation and productivity growth—the lifeblood of a modern society. One need look no further than rural North America in the 1920s and 1930s—regions that were transformed from economic backwaters through active rural electrification programs—to see the importance of electrification as the precursor to economic opportunity and well-being. Further, as electricity's share of "final energy" in the U.S. increased from 7% in 1950 to nearly 20% today, the energy required per unit of GDP dropped by one third. Such important achievements, which occurred throughout the industrialized world, remain elusive in the least

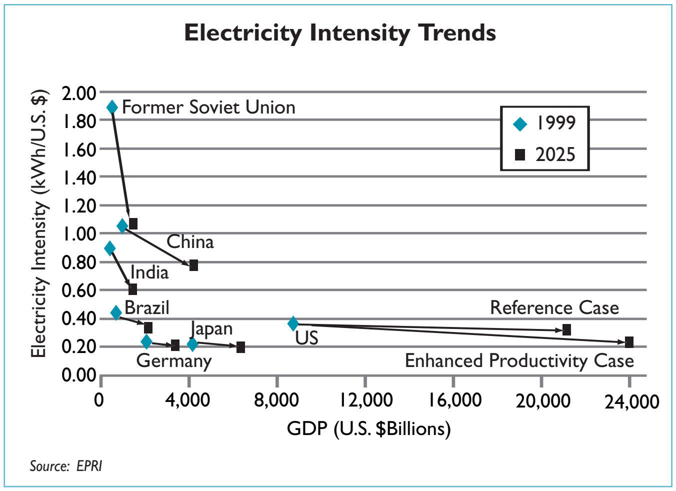


FIGURE 5-5.
Improvements in access to electricity promise significant increases in productivity. Data for the U.S. show both the Reference Case and the Enhanced Productivity Case.

developed world regions. Over the last 25 years, about 1.3 billion people have been connected to electric service, but even this achievement has not kept pace with global population growth. Today, the International Energy Agency estimates that 1.6 billion people lack access to electricity. To keep pace with the world's growing population, electrification must reach at least an additional 100 million people per year for at least the next 50 years. This is about twice the current rate of global electrification.

Setting Electrification Goals

Equally important as universal access to electricity is assuring adequate levels of electric service for those who have access. This Roadmap establishes 1,000 kWh per person per year as a benchmark goal for minimum electric services—an essential milestone in the pathway out of poverty. This target is similar to the electric consumption in emerging modern societies that use a mix of fuels (some directly, others via electricity carrier) to satisfy their needs (see Figure 5-6). It lies between very low levels of electrification (100 kWh per person per year) insufficient for measurable economic benefits and the 10,000+ kWh per person per year of the current U.S. economy. Achieving this target can help meet personal needs for basic lighting, communication, entertainment, water, and refrigeration, as well as provide electricity for the efficient local production of agriculture and goods and services.

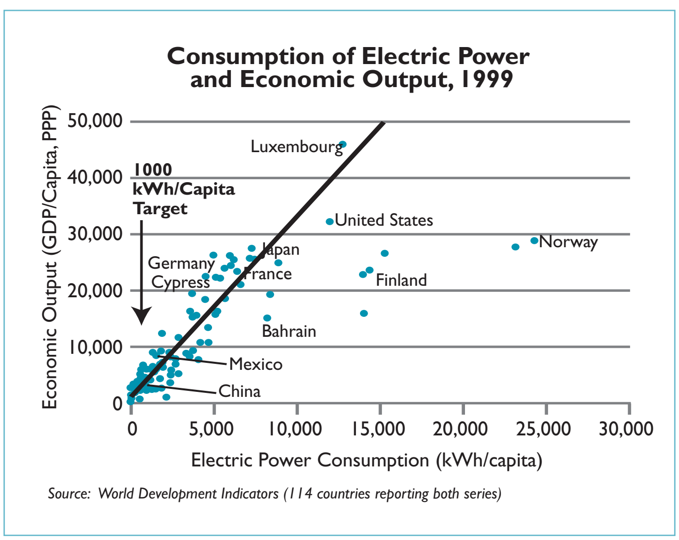


FIGURE 5-6.
Power consumption and economic productivity are correlated.

When choosing the 1,000 kWh per capita per year goal, participants in the Roadmap process were mindful that improved energy efficiency and complementary innovations would allow delivery of basic energy services using less electricity. Nonetheless, the benchmark reveals that, under current trends, perhaps 90% of the world's population in the next 50 years will be born into conditions that fall short of the 1,000 kWh goal. Based on country averages, about 3.7 billion people today live in countries where the average per capita consumption of electric power is below the 1,000 kWh threshold. Over the next 50 years, it is likely that another 3 billion people will be added in these electricity-deficient areas.

Providing power to a global population in 2050 of 9 billion—including minimum levels of 1,000 kWh per person per year to the very poorest people—will require roughly 10,000 GW of aggregate global generating capacity, or three times the current level, based on today's technology. That corresponds with at least a 3% annual rate of increase in global electricity supply. Even with major efficiency gains in the generation and use of electricity, the aggregate global requirements for electricity generation will still be prodigious. Therefore, a critical priority is the development and deployment of an advanced portfolio of clean, affordable, generating technology options—fossil, nuclear, and renewables—that reflects the diverse resource, environmental, and economic realities of the world, while enhancing efficiency and productivity throughout the energy supply chain.

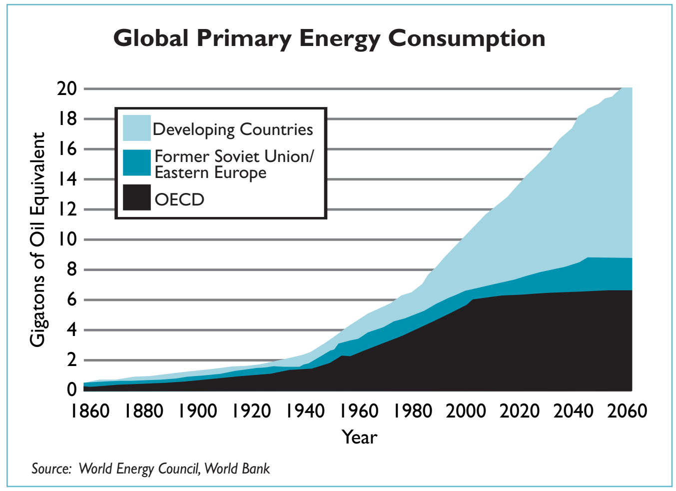


FIGURE 5-7. Advanced generation solutions will be increasingly important to preserving global reserves of primary energies such as oil, coal, etc.

Electrification Boosts Prosperity

Electrification addresses poverty reduction in all its dimensions—not only lack of income, but also the lack of healthcare, education, and control over their lives that poor people suffer. It does this by introducing new efficiencies into the use of energy, labor, and capital for industry, business, and homes. The compounding benefits of electrification are illustrated by the contrast between energy and economic projections by the World Energy Council ("WEC") (Table 5-1) and those necessary for achieving Roadmap goals (Table 5-2).

By 2050, the WEC projects that electricity will provide 35% of final energy in North America, but only 11% of final energy in the developing world. The Roadmap, on the other hand, calls for electricity to provide nearly half of final energy in the industrialized world and at least 30% in the developing countries by 2050.

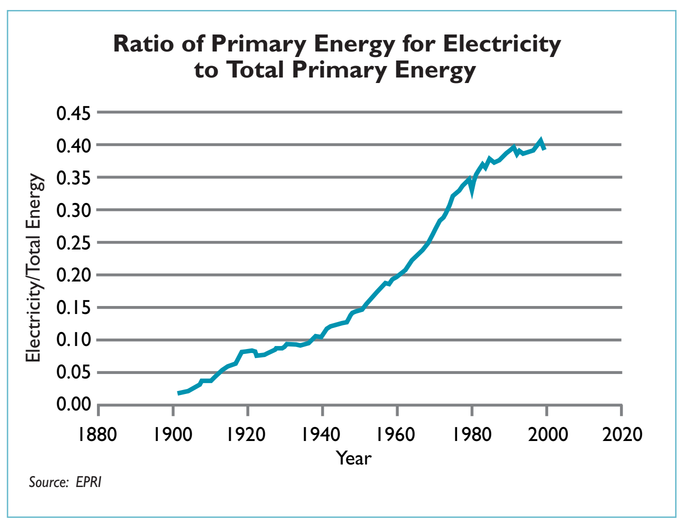


FIGURE 5-8. Primary energy for electricity will continue to increase as generation efficiencies increase and electrification continues.

Table 5-1. WEC Projections for 2050

Regions	Population (Millions)	GDP (10^{12} U.S.$ PPP)	GDP/ Capita (10^3 U.S.$ PPP)	Primary Energy (MTOE)	Primary Energy per Capita (10^3 Cal/Day)	Electricity (% Final Energy)	Carbon Emissions (MTC/Yr)
North America	470	21	45	3,500	210	35	1,900
Western Europe	420	14	33	2,200	140	32	800
Australasia	130	5	38	750	130	33	250
Developed Economies	**1,020**	**40**	**39**	**6,450**	**165**	**33**	**2,950**
Eastern Europe and Former Soviet Union	220	3.0	13.6	1,200	145	14	800
Latin America	750	6.9	9.2	1,800	65	12	750
China/East Asia	1,900	17.0	8.9	4,400	63	12	2,500
Emerging Economies	**2,870**	**26.9**	**10.5**	**7,400**	**69**	**12**	**4,050**
Extended Mid-East	2,350	9.5	4.0	2,900	33	10	1,700
Indian Subcontinent	1,700	4.8	2.8	1,400	21	11	600
Sub-Saharan Africa	1,000	2.0	2.0	750	21	10	400
Developing Economies	**5,050**	**16.3**	**3.0**	**5,050**	**27**	**11**	**2,700**
WORLD	**8,940**	**83.2**	**10**	**18,900**	**57**	**18**	**9,700**

Notes
A. 2050 population figures from International Database—U.S. Census Bureau
B. 2050 GDP computed by applying current rate of increase to 2000 figures
C. Energy and CO_2 values derived from current EIA International Energy Database figures escalated using current growth rates
D. Projected Chinese GDP Growth: 6%/yr 2000–2010, 5% 2011–2020, 4% 2021–2030, 3% 2031–2040, 2% 2041–2050
E. GDP in Year 2000$
F. 1,000 calories/day = 4.2 kilojoules/day
G. The Extended Mid-East region covers Central Asia, the Middle East, North Africa, and Southeast Asia.

Table 5-2. Roadmap Scenario for Global Electrification by 2050						
Regions	**GDP (10^{12} $ PPP)**	**GDP/ Capita (10^3 U.S. $ PPP)**	**Primary Energy (MTOE)**	**Primary Energy/ Capita (10^3 Cal/Day)**	**Electricity (% Final Energy)***	**Carbon Emissions (MtC/Yr)**
North America	21	45	2,400	165	48	800
Western Europe	14	33	1,400	110	46	450
Australasia	5	38	500	100	56	170
Developed Economies	**40**	**39**	**4,300**	**110**	**48**	**1,420**
Eastern Europe and Former Soviet Union	4	18.2	1,100	100	38	520
Latin America	8	10.7	1,400	60	31	550
China/East Asia	25	13.2	3,800	54	31	1,650
Emerging Economies	**37**	**12.9**	**6,300**	**59**	**32**	**2,720**
Extended Mid-East	14	6.0	3,200	36	35	1,500
Indian Subcontinent	9	5.3	1,800	30	26	450
Sub-Saharan Africa	4	4.0	1,000	30	31	350
Developing Economies	**27**	**5.3**	**6,000**	**32**	**31**	**2,300**
WORLD	**104**	**11.7**	**16,600**	**50**	**35**	**6,440**

*Extrapolations are based on the following assumptions about the annual growth rate of electricity as a fraction of final energy over the period 2000–2050:

- Advanced Industrialized World—2.0%
- Emerging Economies—2.5%
- Developing Economies—3.0%

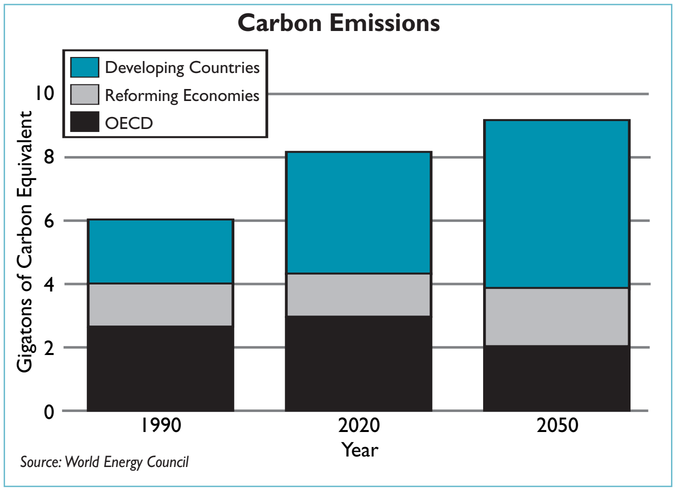


FIGURE 5-9. Improved energy efficiency and low carbon sources of energy are needed to reduce CO_2 emissions.

Electrification Delivers Environmental Benefits

A comparison of the energy and carbon intensities in the two scenarios also shows the benefits of universal electrification. According to WEC's projections, the developing countries will require more than twice the energy to produce a unit of GDP in 2050 than industrialized countries, while emitting more than twice the CO_2 per unit of GDP. In contrast, the 2050 Roadmap target shows: (1) substantially lower energy per unit GDP in the developed world and (2) GDP growth of more than 60% with 50% less carbon emission per unit of GDP in the developing world, relative to WEC projections.

The greater diffusion of electric technologies not only benefits the households that are connected and helps protect the environment, but it also has multiplier effects on the economy. Households and firms connected to electric service are more readily integrated into a wider range of other modern services, and they are fuller participants in the economically productive aspects of modern societies.

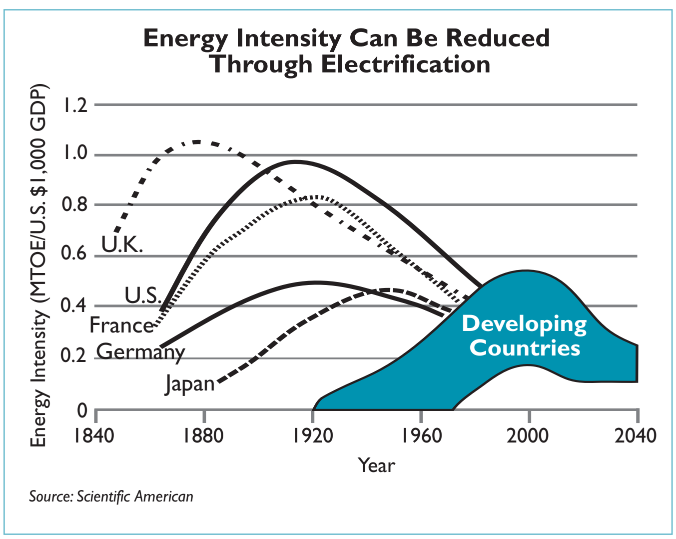


FIGURE 5-10. By "leapfrogging" to new generation technologies, developing countries can reduce energy intensity faster than historical trends.

Leapfrogging to Higher Levels of Energy Efficiency

One of the key benefits of electrification is the ability to pursue continuous improvements in energy efficiency. Technological progress should allow the developing nations to leapfrog over the less-efficient historic economic development pathways taken by today's affluent nations. These nations all followed a very similar developmental trajectory, using increasing amounts of energy per dollar of goods and services (i.e., increasing energy intensity) in the initial stages of industrial development, then peaking, and ultimately experiencing a steady decline in energy intensity, fostered in large part by the electrification of their economies. Most important for the future, the peak energy intensity for industrial development has been successively lower for each new nation passing through the same economic stages through use of increasingly efficient technologies. Electrification is essential if developing nations are to maintain this trend of increasing resource efficiency in the global economy.

The Payoff of Electrification

The benefits accruing from initial access to electricity, beyond creating economic opportunities, are broadly two-fold: first, a fundamental reduction in levels of pollution, both indoor and outdoor; and second, the freeing up of time through the substitution of commercial energy for manual labor. Experience demonstrates that this energy substitution can enable education, which, in turn, can promote more stable families, lower population growth rates, and allow for a more productive work force. Successful energy programs in rural areas, where the majority of those now denied access to electricity live, may also lighten the pressure to leave the countryside for cities. However, there are no simple cause-and-effect relationships between electrification and geographical moves of population.

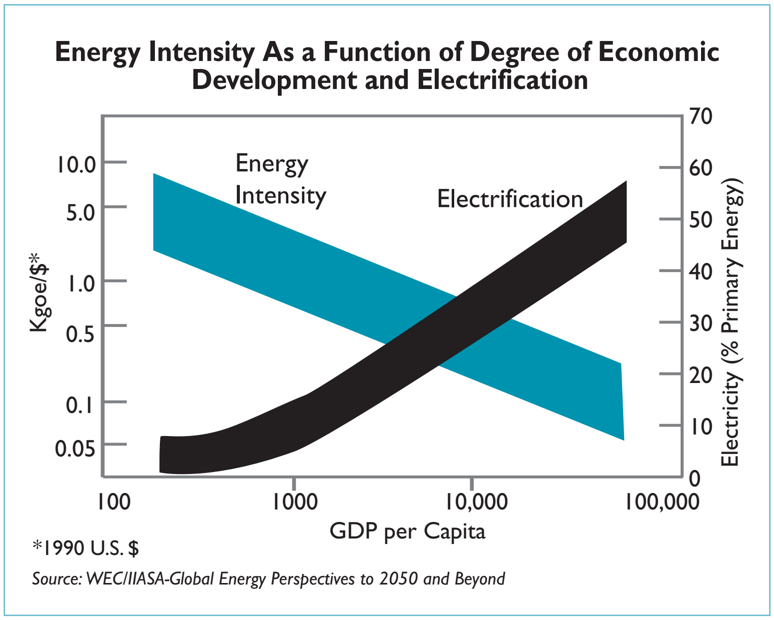


FIGURE 5-11. Electrification promotes economic development and prosperity.

Most of those who are currently under-served by electricity live in rural areas, and meeting their needs will require technological choices that are different from those for urban electrification. For example, the decentralization of electric generation is particularly important in these rural areas because of the high cost of electricity distribution infrastructure. Decentralization can occur in terms of supply (e.g., mini-grids supplied with renewable energy such as biogas) as well as demand. Important technical and economic issues with these decentralized systems include the allocation of investment between generation and distribution infrastructure on the one hand, and improving efficiency and end-use load profiles on the other.

Global data indicate a robust relationship between electric power consumption and economic growth, with each kWh consumed adding about $3 to the local economy. This suggests that electrifying the world is not only essential to eliminating poverty, but also crucial for "lifting all boats." Although averages and correlations can be deceiving, the tight relationship between electricity and economic output is striking. The average per capita income in the world today is equivalent to about $5,500/year. If average incomes rise at 3% a year over the next 50 years, then average annual electricity consumption worldwide would rise to about 9,000 kWh/capita based on current technology. China's performance in this area is notable. Its annual electricity consumption doubled from 550 billion kWh to 1,100 billion kWh during the 1990s, while the population grew by only 10%. Based on an anticipated world population of about 9 billion in 2050, electric energy requirements would be approximately 80,000 TWh, or more than four times global consumption today. However, the energy consumption requirements can be reduced through supply-side and demand-side efficiency

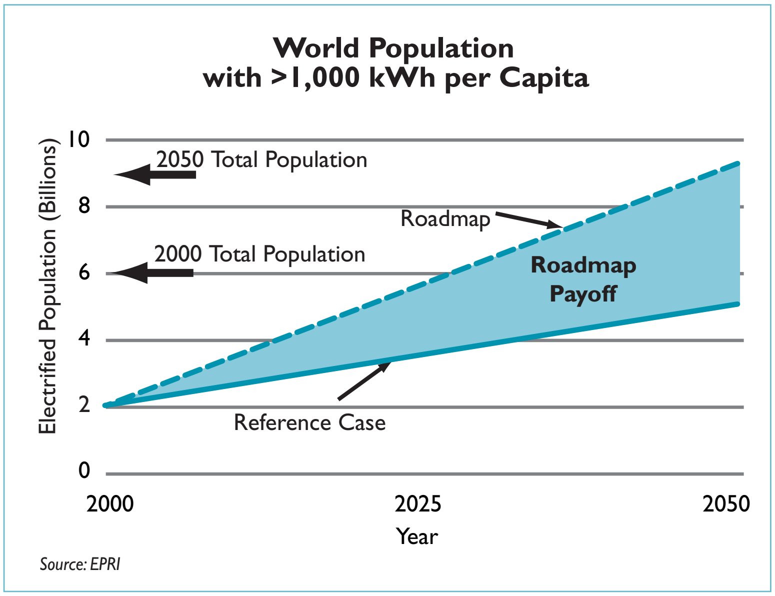


FIGURE 5-12. Under the Roadmap scenario, everyone will have access to enough electricity to achieve basic levels of social development. This could jump start the economies of the developing world.

improvements. For example, reducing per capita electricity by one third—as in the Roadmap scenario for global electrification—would reduce total electric energy to about 55,000 TWh, close to the estimate of 60,000 TWh of the 1999 Roadmap.

The benchmark of providing no less than 1,000 KWh/capita provides a useful approach for assessing the payoff of the Roadmap. As Figure 5-12 shows, currently about 40% of world population meets this benchmark. However, extending this level of service to the global population of 9 billion in 2050 would require adding service for well in excess of 100 million persons per year for the next 50 years.

Conclusion

It is essential that the task of electrifying the world not be viewed in isolation from other development challenges. The numerous people who lack access to commercial energy are essentially the same people who lack access to education and sanitation, are condemned to extreme poverty, and are the main sources of global population growth. From 1970 to 1990, in the developing regions where economies grew substantially (Latin America and China), about 650 million people were connected to electric power service, while the corresponding population grew by only 280 million. That striking achievement is especially linked to economic growth in China, where township and rural economic growth occurred in lockstep with electrification. In contrast, in regions where economies and institutions fared poorly (Africa and the Indian subcontinent), additional population outpaced new electrical connections by about 250 million people.

In summary, better access to energy, particularly in the form of electricity, is essential to improving the quality of life for billions of people, and, when coupled with complementary technology initiatives, electricity is the foundation for a global sustainable development strategy. Using electricity-based energy carriers that are cleaner and more flexible than traditional fuels will help societies meet four inextricably linked global needs: (1) the protection and restoration of earth's life-support systems, (2) managing resources crucial to human welfare, (3) elimination of human poverty, and (4) stabilizing the global population.

CHAPTER

6 LIMITING CHALLENGES

The 14 Limiting Challenges Studies

1. Transmission capacity, control, and stability
2. Infrastructure to power a digital society
3. Robustness and security of electricity infrastructure
4. Value of energy storage technologies
5. Transforming electricity markets
6. Electricity-based transportation systems
7. High-efficiency end uses of electricity
8. Advances in enabling technologies
9. Strengthened portfolio of generation options
10. Universal global electrification
11. Carbon capture and storage technologies
12. Ecological asset management
13. Improving water availability and quality
14. Environmental science

This Roadmap's strategic R&D recommendations are largely derived from a series of 14 topical studies conducted in 2002 by a combination of EPRI senior technical staff, consultants, and reviewers from other organizations. Those topical studies, termed the "Limiting Challenges," were based on an industry-wide effort led by EPRI to identify the issues of greatest concern in assuring electricity's optimal service to the world and its peoples. (Figure 6-1 shows how the Limiting Challenges relate to one another as well as to the five Roadmap Destinations.) The dates in Figure 6-1 and the other logic flow diagrams in this section represent technology readiness.

The topics covered in the Limiting Challenges studies were selected through a combination of staff proposals, industry symposia, and outreach to other interests. Many other topics were considered, but these final 14 were ultimately judged to be the most critical, based on strategic importance in moving the world toward the Roadmap's vision of health, opportunity, and security for all in a sustainable global environment. This chapter presents summaries of the results of each of those studies.

The Limiting Challenges Studies

Within each of the Limiting Challenges, several "critical capability gaps" (CCGs) were identified during the selection process. The CCGs represent the issues judged to be most intractable or underfunded in present and planned R&D worldwide, and provide an organizational framework for each topical study. From three to seven CCGs were identified for each Limiting Challenge. All of the Limiting Challenges studies were designed to address a series of key questions:

- What is the current situation and basic challenge?
- What R&D is already in progress or planned?
- What is the comprehensive R&D strategy needed to resolve the CCGs and meet this Limiting Challenge?
- What is the approximate cost and schedule for that R&D program? (Table 6-1 summarizes funding requirements for each Limiting Challenge.)
- What organizations should be involved in the needed R&D and its support, and how?

The Limiting Challenges reports are available for review at epri.com.

FIGURE 6-1.
The Roadmap describes a logical progression of R&D tasks necessary to achieving global sustainability.

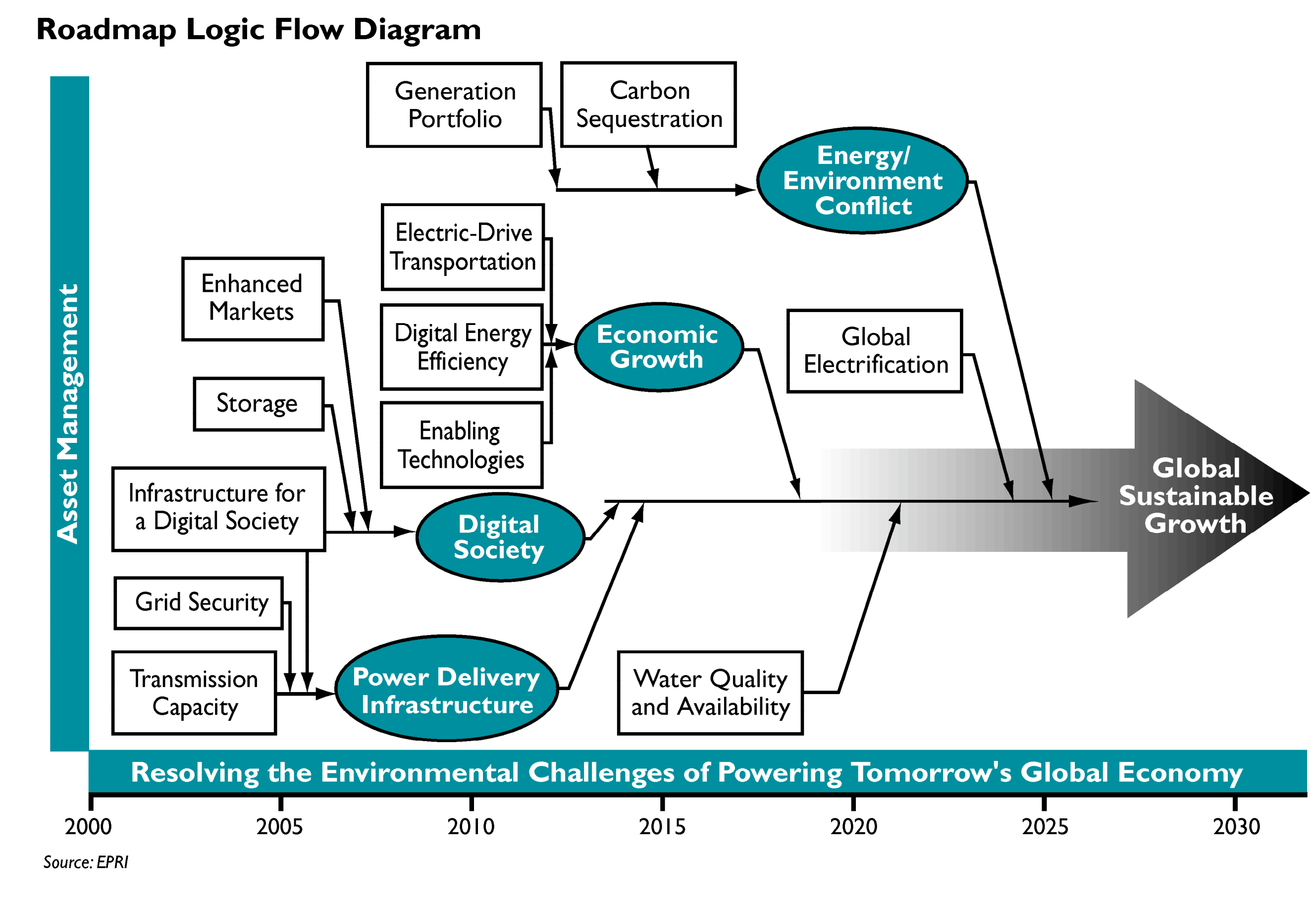


Table 6-1. Research, Development, and Demonstration Funding Needed to Address Limiting Challenges			
LC Number	**Title**	**Current Funding[1] (U.S. $ Million/Year)**	**Roadmap Funding Recommendations[1] (U.S. $ Million/Year)**
1	Transmission capacity, control, and stability	$200	$1,000
2	Infrastructure to power a digital society	$800	$2,500
3	Robustness and security of electricity infrastructure	$10	$300
4	Value of energy storage technologies	$50	$100
5	Transforming electricity markets	$100	$150
6	Electricity-based transportation systems	$100	$200
7	High-efficiency end uses of electricity	$400	$600
8	Advances in enabling technologies	$500	$1,000
9	Strengthened portfolio of generation options	$700	$2,300
10	Universal global electrification	NA	$400
11	Carbon capture and storage technologies	$200	$300
12	Ecological asset management	$10	$50
13	Improving water availability and quality	$50	$100
14	Environmental science	$700	$900
	TOTAL	**$3,820**	**$9,900**

[1]Includes public and private funding

Summaries of the Limiting Challenges

The remainder of this chapter summarizes the 14 Limiting Challenges reports. Each summary provides a brief topical overview and some emerging solutions, followed by an outline of the recommended approach to each CCG, its estimated cost and timing, and a graphical interpretation of the medium-term R&D timeline for that Limiting Challenge.

The costs shown in the summaries are estimated average annual costs required to begin meeting all the R&D needs identified in each Limiting Challenges study. These cost estimates apply to the first decade of the Roadmap's R&D program. A rapid ramping-up of technical capabilities and resources will be required to meet the increased levels of R&D effort proposed. Most topical R&D is assumed to continue after that decade at similar magnitudes but with less predictability. By 2020, R&D will continue, but the dominant effort is anticipated to shift from R&D on these challenges to broad commercial deployment, with the ultimate goal of global infrastructure transformation by mid-century.

These topical summaries are intended only to suggest the direction and scale of the required R&D. We hope they provide a starting point for discussion and refinement among major governmental and private research organizations as well as public policy developers and investors.

LIMITING

CHALLENGE I

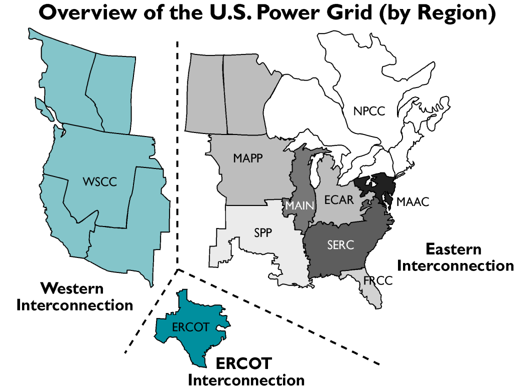
Transmission Capacity, Control, and Stability

Today's transmission grid does not provide the capacity, control, or stability required to meet critical 21st century challenges, such as increasing power availability and reliability, ensuring power quality, and improving power security. A comprehensive *transmission grid expansion plan* will help to identify and prioritize areas of greatest need. A *wide-area measurement system* will support enhanced grid monitoring, providing the data that other systems will require to identify possible trouble or respond to events. A *self-healing grid system* will offer instantaneous response to changes in market conditions as well as natural and man-made events.

The Need for Increased Transmission Capacity, Grid Control, and Stability

The North American power grid, "the most complex machine ever invented," consists of four regional systems, each of which is a complex, integrated web of transmission lines, distribution systems, and power plants. With demand for electricity increasing at an annual rate of 1.5–2% each year and rapid spreading of digital technologies that require ultra high-quality electricity, the strain on this power grid is beginning to show. On August 14, 2003, an outage interrupted power to 50 million people in eight U.S. states and two Canadian provinces causing losses estimated as high as $3 to $10 billion. The many small generation and storage devices (distributed energy resources, or DER) now appearing throughout the grid must be integrated into the existing system to assure optimum operation. And today's facilities are aging, performance is declining, and maintenance requirements are rapidly increasing.

Overview of the U.S. Power Grid (by Region)



Source: North American Electric Reliability Council

FIGURE 6-2. Replacing the aging systems that make up today's power grid is critical to improving power quality and reliability.

Emerging Solutions

Major upgrades are necessary to provide power service at the level of reliability already required by many customers. More will be required to meet forecast needs for power quality, reliability, security, and availability at low cost. The first step is the completion of regional and national plans for power grid expansion and enhancement. Then a broad range of new technologies will be required to allow the system to work as needed. Component-level innovations, such as composite materials, embedded fiber optics, and high-strength cables, will offer enhanced reliability. Power electronics-based integrated network control (using new post-silicon power electronics) promises to increase the capacity of transmission lines and improve overall system reliability. A self-healing grid system will be much more responsive to changes in electricity demand as well as to natural and man-made events. Wide-area measurement systems on the national level will provide critical data required by the self-healing system as well as by new security systems.

Funding Requirements

R&D initiatives necessary for developing urgently needed transmission grid infrastructure will require approximately $1 billion per year over the next 10 years.

MOST CRITICAL R&D NEEDS:
For Increasing Transmission Grid Capacity, Grid Control, and Stability

Regional and Continental Power System Expansion Planning

- *Critical needs:* Plan for expanding and enhancing the North American transmission grid; planning tools to model uncertainties, such as location, size, and timing of new power plants, interregional power transfer patterns, etc.; online congestion-monitoring systems
- *Approach:* Incorporating results of DOE's 2002 National Transmission Grid Study; a plan for developing new transmission planning tools and online congestion-monitoring systems

Grid Automation

- *Critical needs:* Integrated energy and communications system architecture to enable development of interoperable components; fault anticipation technology to forecast grid failures; adaptive islanding and storage plant damping pilot tests; intelligent network agents pilot test
- *Approach:* A multi-phased R&D plan; coordination with Wide-Area Management Systems (WAMS) and other relevant projects

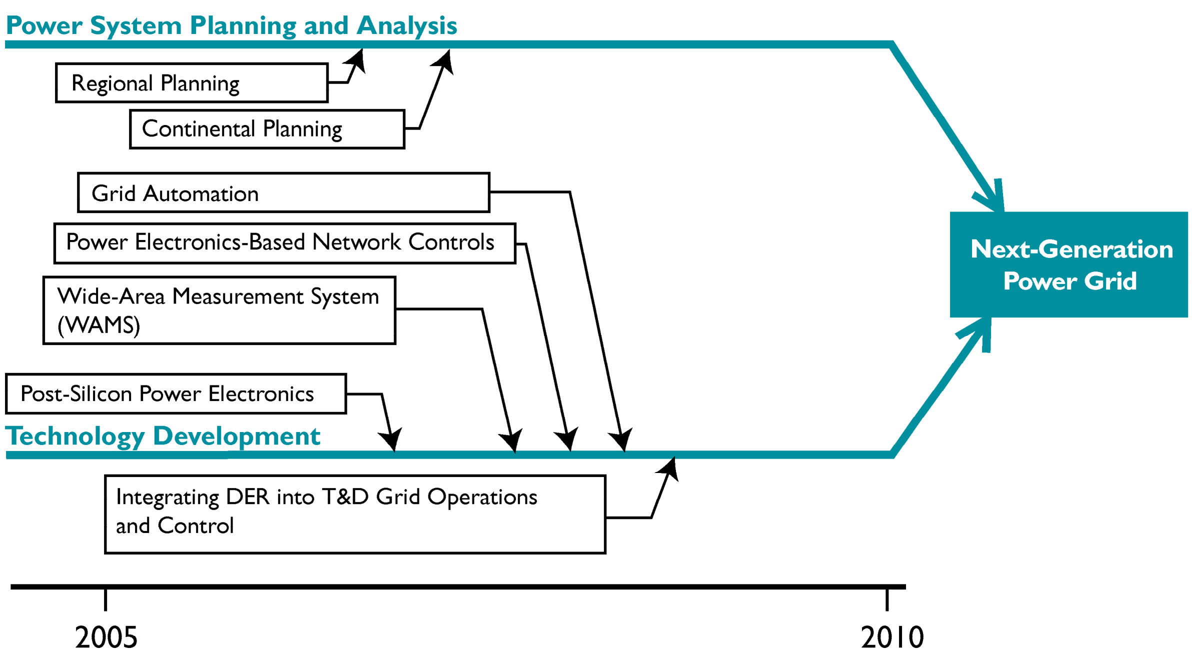
Integrating Distributed Resources into T&D Grid Operations and Control

- *Critical needs:* Secure communications and control system; sophisticated models to measure and predict customer demand; assessment of compatibility between DER devices and the existing grid; specification of advanced interconnection requirements
- *Approach:* A multi-phased R&D plan; recruiting technology vendors and DER end-users to participate in technology development and demonstration

Additional Critical Capability Gaps

- Wide-Area Measurement System (WAMS)
- Power Electronics-Based Network Control
- Post-Silicon Power Electronics

Increasing Transmission Capacity, Control, and Stability R&D Logic



Source: EPRI

FIGURE 6-3. This chart illustrates key milestones on the road toward improved transmission grid capacity, control, and stability.

LIMITING

CHALLENGE 2

Infrastructure to Power a Digital Society

Over the next 20 years, today's electric power systems will undergo a dramatic transformation to meet the digital economy's rapidly growing demand for premium power. *Advanced end-use technologies* and *backup generation systems* are needed to minimize the impact of power quality fluctuations. *New microgrid options* and *integrating microgrids with existing transmission systems* will reduce the number and severity of power disturbances, thereby improving power security, quality, reliability, and accessibility (SQRA) for increasingly demanding electricity consumers. An *intelligent, self-healing power grid* would improve overall system capacity and power reliability, while the *integration of distributed resources* with this grid could produce a less centralized power system resistant to natural and man-made disasters. *New digital technology* opportunities will address the convergence of electricity and telecom systems and give customers more control over how they buy electricity.

Demand for premium electricity may increase from 10% today to as much as 50% over the next 20 years.

Tomorrow's Power Quality and Reliability Needs

The Northeast Blackout of August 14, 2003 once again brought worldwide attention to the issues of electric power infrastructure SQRA. But many people don't realize that, in the U. S., some 500,000 customers lose power each day for an average of 2 hours, and that the number of customers affected by momentary interruptions and voltage sags is even greater. These shorter duration events are most important for industrial customers. Power disturbances ranging from milliseconds (momentary voltage sags) to several seconds can significantly impact industrial processes. A 1/10th of a second event can cause a petrochemical refinery to shut down or a semiconductor processing plant to stop production. Once interrupted, it often takes hours for these facilities to get back to normal production. On any given day in a year, approximately 30,000 industrial customers are impacted by such power disturbances.

Over the next two decades, the global economy will increasingly depend on the integrity of complex interactive networks, including the Internet, telecommunications, and electric power systems. All of these critical networks rely on digital devices that are sensitive to very small fluctuations in electricity quality. According to EPRI research, the demand for premium electricity may increase from 10% today to as much as 50% over the next 20 years.

Today's power infrastructure (including integrated transmission, distribution, and generation capabilities) is not sufficient to deliver high-quality digital-grade electricity at a reasonable price. Utilities are already struggling to meet both current electricity demand and (in the U.S.) the challenges of deregulation with aging systems. The electricity delivered via these systems is inherently subject to potentially disruptive power quality disturbances, such as voltage sags and swells, switching surges, poor voltage regulation, harmonics, etc. As a result, the cost of premium power quality and reliability delivered over the existing power grid is high and getting higher.

Although there are some short-term options for increasing the throughput of the current infrastructure—such as equipment life extension and changing transmission schedules—meeting tomorrow's demand for ultra-reliable electricity will require the transformation of today's power grid into an intelligent "energy web" capable of delivering ultra high-quality power and responding to industry's changing needs.

Finding solutions to improve the performance of the delivery infrastructure must be considered in combination with the requirements and designs of end-use equipment and processes. A radical change to achieve compatibility between the grid infrastructure quality and reliability and the design of end-use technologies and processes is needed. This compatibility will be achieved not only by developing new, advanced technologies to improve the performance of the power supply system, but also by identifying market and regulatory structures that could facilitate flexible and tailored quality and reliability levels as a function of system and customer types and contractual arrangements.

Emerging Solutions

Short to Medium Term

For many organizations, distributed energy resources (DER) may offer a lower-cost alternative to meeting the SQRA requirements. For commercial electricity consumers, integrated DER can provide a power supply that is less vulnerable to attacks on the central public power system while reducing electricity costs. For T&D utilities, integrated DER may allow deferred infrastructure expansion and reduced power system losses. For generation companies, integrated DER can support the addition of renewable energy—which can offer emission credits, fuel security, and enhanced marketing value—to their portfolios. For society as a whole, a less centralized power system is more resistant to man-made and natural disasters.

To accommodate the increasing use of DER, it will be necessary to integrate DER with existing power systems. To accomplish this, significant R&D will be required to connect DER to existing distribution systems and to minimize voltage sags and service interruptions.

Long Term

Transforming today's power grid will require the development, testing, and deployment of several new technology types. The cornerstone of this infrastructure will be a self-healing and intelligent grid control system. This system will automate power distribution, allowing instantaneous response to changes in power demand, potentially disruptive conditions, and security issues. In addition, tomorrow's power grid will rely on the integration of distributed resources—through AC and DC microgrids—with existing systems. This will enable the intelligent grid control to respond to demand spikes. And new digital technologies will make it possible to control, or even eliminate, electromagnetic interference, manage the convergence between telecommunications and electrical systems, and better understand the interaction between electric power systems and digital devices.

Funding Requirements

R&D initiatives necessary to support tomorrow's digital economy will require approximately $2.5 billion per year over the next 10 years.

MOST CRITICAL R&D NEEDS:
For Building the Infrastructure of a Digital Society

Self-Healing and Intelligent Electrical Grid Systems

- *Critical needs:* Designing and testing prototype automated distribution systems; commercializing high-temperature superconducting T&D systems; assessing the viability of multi-purpose utility corridors; designing and testing new security measures; improving response to common-mode failure mechanisms
- *Approach:* R&D to develop and enhance self-healing grid technologies; demonstrations at generation and T&D sites; public/private partnerships

Integration of Distributed Resources

- *Critical needs:* Defining, designing, and implementing AC microgrids; introducing DC microgrids into grid architecture; implementing DER on AC and DC distribution systems
- *Approach:* R&D to develop and enhance AC/DC grid technologies; demonstrations at generation and transmission and distribution sites; public/private partnerships

AC and DC Microgrids

- *Critical needs:* Designing and testing AC and DC microgrids; interconnecting AC and DC microgrids with each other and with existing transmission infrastructure
- *Approach:* R&D to develop and enhance microgrid technologies; demonstrations at T&D sites; public/private partnerships

Environmentally Acceptable Distributed Energy Resources

- *Critical needs:* New backup system designs; intelligent switchover mechanisms; rapid power-up and power-down sequences; integration with existing grid infrastructure
- *Approach:* R&D to develop and enhance backup generation systems; demonstrations at generation and T&D sites

Power Quality Solutions for End Users

- *Critical needs:* Designing and testing end-use devices that are less susceptible to electromagnetic interference, including a variety of digital technologies; designing and testing adaptors capable of "filtering out" voltage sags and spikes
- *Approach:* R&D to develop and enhance power quality technologies; application of power quality solutions to a wide variety of industries

Digital Technology Opportunities

- *Critical needs:* Designing technologies to control/eliminate electromagnetic interference; hardening end-use devices; addressing technology and policy issues associated with "last mile" convergence of telecommunications and electricity systems; improving the current level of knowledge surrounding the effects of power systems on digital devices

• *Approach:* R&D to develop and enhance relevant digital technologies; demonstrations at generation and T&D sites; public/private partnerships

Emergency Control and Restoration

• *Critical needs:* Software to propose alternative system reconfigurations, analyze the dynamics of T&D systems, and automate grid reconfiguration; secure communications infrastructure; advanced sensors; intelligent network agents

• *Approach:* Fast-track R&D funding; rapid implementation plan

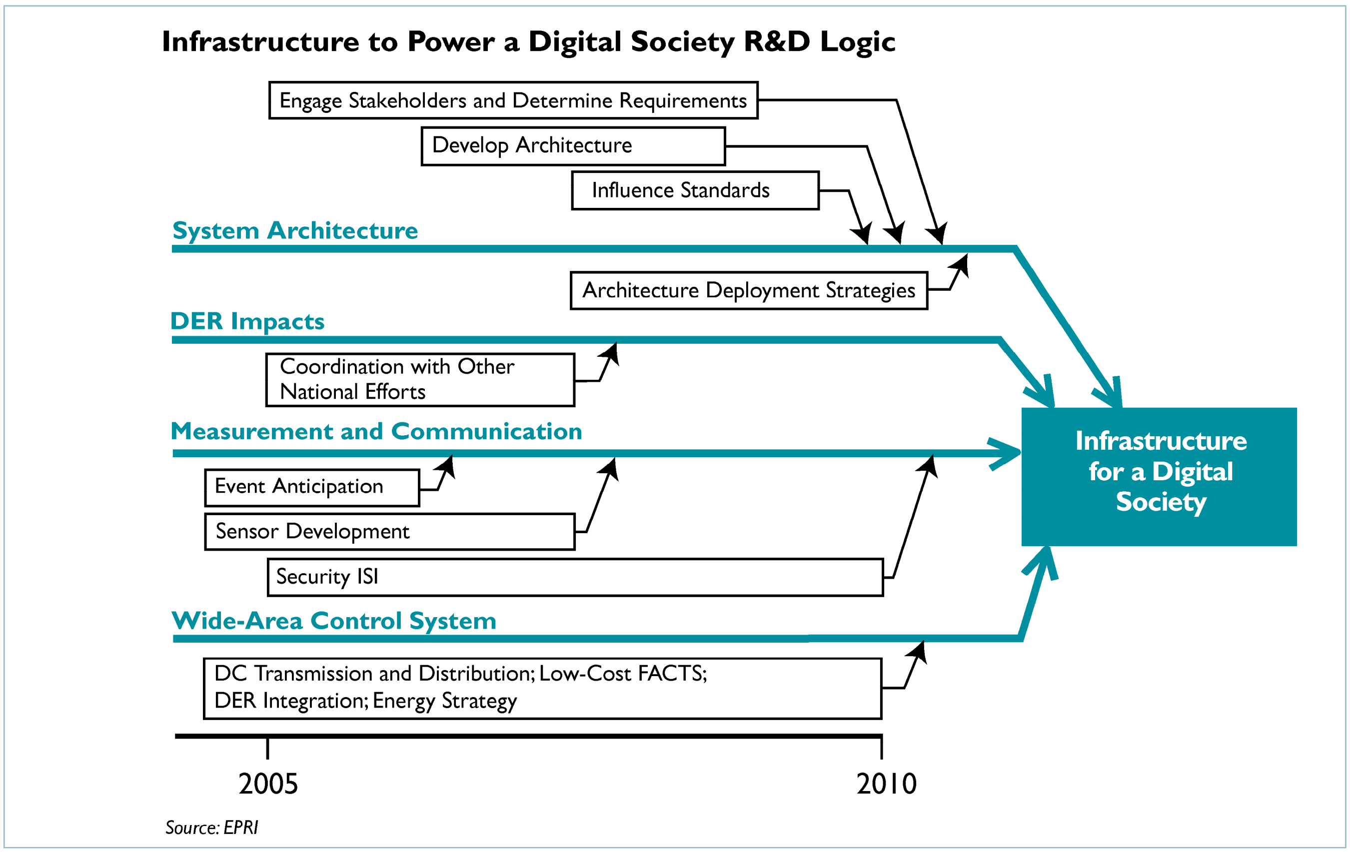


FIGURE 6-4. This chart illustrates key milestones—given sufficient funding—on the road toward building the infrastructure for tomorrow's digital society.

LIMITING

CHALLENGE 3

Robustness and Security of Electricity Infrastructure

A man-made or natural disaster that disrupts electricity supply and delivery could have destructive effects on national security, the economy, and the lives of every citizen. A thorough *probabilistic vulnerability assessment* will help to identify security risks and prioritize critical susceptibilities. A *secure wide-area communications network* will provide essential monitoring and control function and improve the availability of information for system recovery. *Emergency control and restoration* systems will ensure rapid recovery from disruptions by coordinating adaptive islanding and grid self-healing.

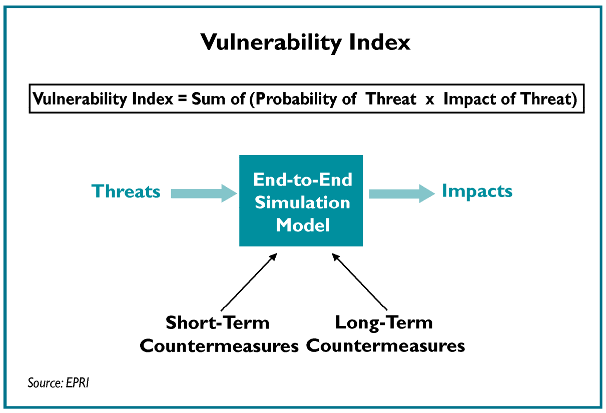


FIGURE 6-5.

Evaluating power system vulnerability to a variety of threats is important to prioritizing power system upgrades.

Tomorrow's Need for Innovative Energy Security Solutions

After September 11, 2001, the security of fundamental infrastructure cannot be taken for granted. The U.S. power system has emerged as one of the most critical challenges for security experts. A recent EPRI assessment developed in response to the September 11 attacks highlights three different kinds of threats to the U.S. electricity infrastructure:

- Attacks *on* the power system, in which the infrastructure itself is the primary target
- Attacks *by* power system components as weapons to attack the population
- Attacks *through* the power system take advantage of power system networks to affect other infrastructure systems, such as telecommunications

Moreover, natural disasters and equipment failures can also cause significant impacts to large segments of the transmission network. All significant outages can have serious economic consequences. Economic damages associated with disrupted services can reach $1.5/kWh (or more), depending on the length of the outage, the types of customers affected, and a variety of other factors.

Emerging Solutions

Close public/private collaboration is required to design and deploy advanced security technologies that address a range of security issues, from preventing attacks before they occur to rapidly recovering after an event, whether natural or intentional. The first step is a vulnerability assessment that evaluates and prioritizes susceptibilities and countermeasures. To reduce vulnerabilities, a secure, wide-area communications system would replace the Internet for critical monitoring and control functions. To support a rapid and effective response to an attack or natural calamity, a Strategic Power Infrastructure Defense (SPID) system could analyze information about the status of the power and communication systems, and coordinate their use for adaptive islanding—the creation of self-sufficient islands in the power grid adapted to make best use of available resources. Assuming a stable system of grid islands is established, a self-healing grid could be used to gradually bring the power system back to its normal state as resources become available.

Funding Requirements

R&D initiatives necessary for developing urgently needed security infrastructure will require an estimated $300 million per year over the next 10 years.

MOST CRITICAL R&D NEEDS:
For Improving Electricity Infrastructure Robustness, Resilience, and Security

Probabilistic Vulnerability Assessment

- *Critical needs:* Developing integrated simulation models capable of modeling the potential impact of threats anywhere along the electricity supply chain; developing a methodology for identifying relative probabilities of threats; developing "pricing" models capable of quantifying the impact of power system events
- *Approach:* Recruitment of experts to set assessment priorities; collection of existing models and historical data that may support vulnerability assessment efforts; development of fast-track implementation plan

Fast Simulation and Modeling

- *Critical needs:* Pattern-recognition and diagnostic models to determine the location and nature of suspicious events; adaptive load forecasting techniques and technologies; improved grid optimization and control
- *Approach:* The rapid development of an R&D plan involving appropriate governmental organizations as well as T&D utilities; pilot system demonstrations

Emergency Control and Restoration

- *Critical needs:* Software to propose alternative system reconfigurations, analyze the dynamics of T&D systems, and automate grid reconfiguration; secure communications infrastructure; advanced sensors; intelligent network agents
- *Approach:* Fast-track R&D funding; rapid implementation plan

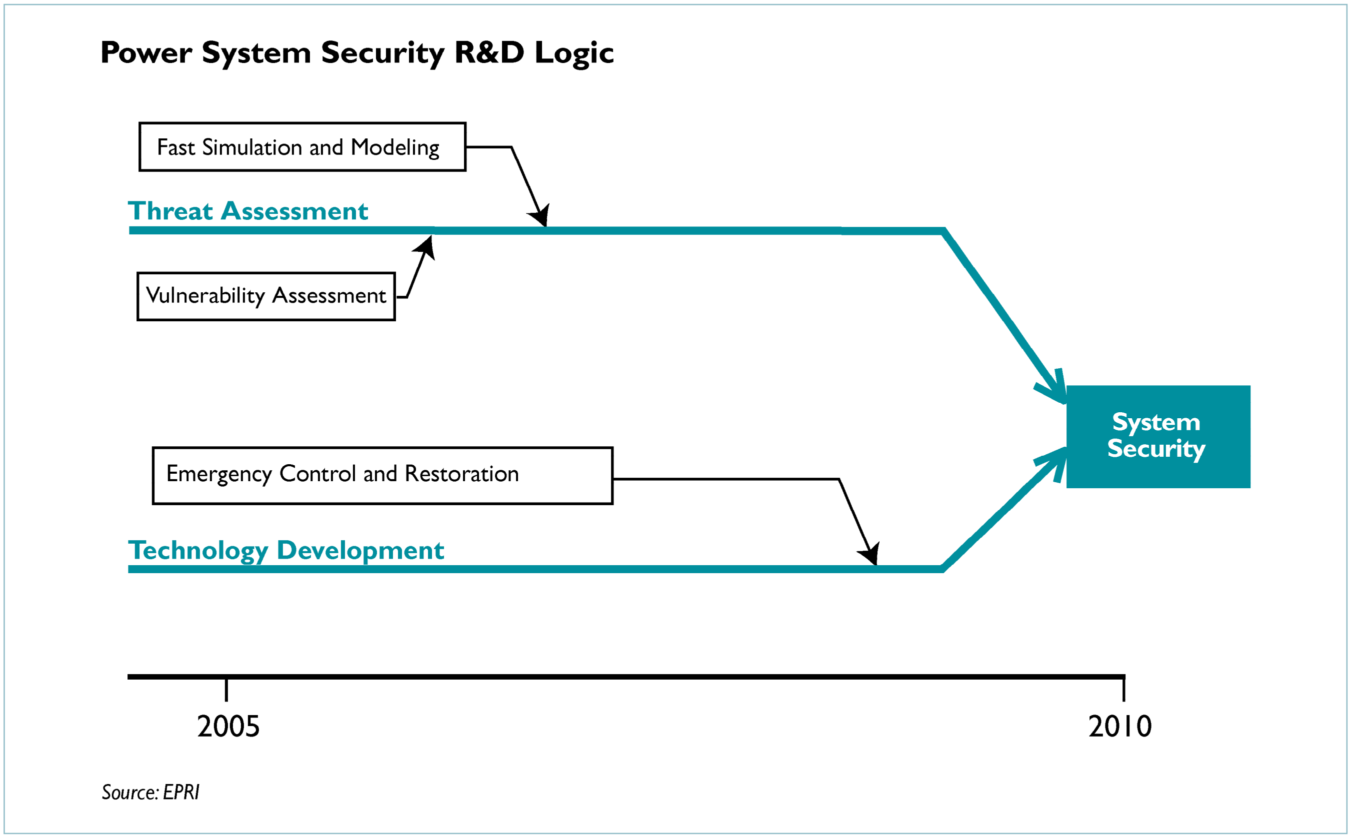


FIGURE 6-6. This chart illustrates key milestones on the road toward improving the robustness, resilience, and s e c u r ity of the electricity infrastructure.

LIMITING CHALLENGE 4

Value of Energy Storage Technologies

Advanced electricity storage technologies promise to change the nature of the power market. They will give power producers much greater financial and operational flexibility, enable grid operators to resolve network bottlenecks and transients, and enhance intermittent renewable power resources. A *cost-benefit assessment of existing and new storage options in today's semi-regulated industry* is a critical first step. *The development and demonstration of more cost-effective high-capacity storage options*—including compressed air, battery, super-capacitors, flywheel, hydrogen, and superconducting systems—will support an "inventory"-driven electricity marketplace that responds to CO_2 and oil import issues.

Tomorrow's Need for Energy Storage

Unlike other energy forms, electricity cannot be easily bottled, boxed, or warehoused when demand is low, and dispensed to meet customer demand. Without an "inventory" to draw upon, utilities have little flexibility in managing electricity production and delivery. Likewise, intermittent renewable resources—such as solar and wind—cannot be relied upon for hourly electricity supply. Although some advanced technologies now exist to store electricity by converting and storing it in another energy form—such as in pumped storage, compressed air, and batteries—today, only about 2.5% of North American generation capacity uses such plants. This is because most storage options (except pumped hydro and compressed air) are relatively unproven, their value proposition is complex and poorly understood, and the uncertainties of changing regulatory rules makes storage options too risky for most investors.

Although some advanced technologies now exist to stock electricity by converting and storing it in another energy form—such as in pumped storage, compressed air, and batteries—today, only about 2.5% of North American generation capacity uses such plants.

Emerging Solutions

Public and private organizations must collaborate to analyze the costs and benefits of existing storage options, including pumped hydro, compressed air, and battery plants. Additional work must consider the potential return-on-investment (ROI) of enhancing existing storage options and building new ones. Achieving these goals will involve the development of new technologies (e.g., for hydrogen storage) and sophisticated tools to predict the costs of large-scale storage systems 5 to 20 years in the future. It will also require new models to simulate the economic characteristics of future grid conditions to predict the potential benefits of storage options to generation, transmission, and distribution owners as well as to end-use customers. Once accurate cost, benefit, and ROI estimates are available, the next step will be a series of R&D projects designed to build large-scale, lower-cost storage modules and demonstrate them at appropriate utility sites under real-world conditions. Over the medium to long term, these efforts should include demonstration of high-pressure hydrogen storage to support the expected evolution of the electricity/hydrogen economy, which will likely have a significant hydrogen-powered transportation sector. During these demonstrations, the collection and analysis of cost and performance data will be a high priority. Finally, to address investor concerns about existing or new storage options, high-end communications to key industry stakeholders will be essential. These communications need to identify and quantify the numerous business opportunities for electric (and gas) utilities in the energy storage area.

Funding Requirements

R&D initiatives necessary for enhancing existing storage options and developing new ones will require an estimated $100 million per year over the next 10 years. This figure does not include the cost of developing end-use equipment, such as hydrogen-fueled autos.

MOST CRITICAL R&D NEEDS:
For Exploiting the Strategic Value of Energy Storage

Establishing the Value Proposition for Storage Options in the North American Market

- *Critical needs:* A detailed assessment including costs and benefits of existing storage technologies; analysis and software capable of estimating future costs associated with the large-scale production of existing and new storage technologies; models capable of simulating future regulatory scenarios; and models simulating the benefits of implementing energy storage options for the multiple types of storage applications within the electricity infrastructure
- *Approach:* Establishing a plan for the assessment of existing storage technologies; developing and testing cost estimates and scenario creation models for appropriate regulation

Improving Cost and Performance of Components and Integrated Storage Systems

- *Critical needs:* Development of large-scale and lower-cost storage systems, focusing on newer technologies, such as flow batteries, sodium sulfur batteries, flywheels, and super-capacitor options; demonstration of these technologies at utility and industry locations
- *Approach:* Developing a long-term R&D plan; recruiting utilities and other industry stakeholder organizations to host demonstrations and participate in documenting costs and benefits

Validating Cost and Performance of Storage Options through Demonstrations

- *Critical needs:* Collecting and analyzing performance data generated during technology demonstrations, which will include enhancement to existing technologies as well as the development of new storage options
- *Approach:* Developing data collection and validation methodologies; working with demonstration host companies to ensure non-disruptive data collection during plant operation for a wide variety of real-world utility conditions

Communicating R&D Results to Appropriate Stakeholders in the Utility Industry

- *Critical needs:* Compiling cost and performance data into intelligible reports; creating "executive level" materials suitable for a wide audience, including the trade media
- *Approach:* Development of a publication schedule and a media plan as well as conferences and workshops, where appropriate

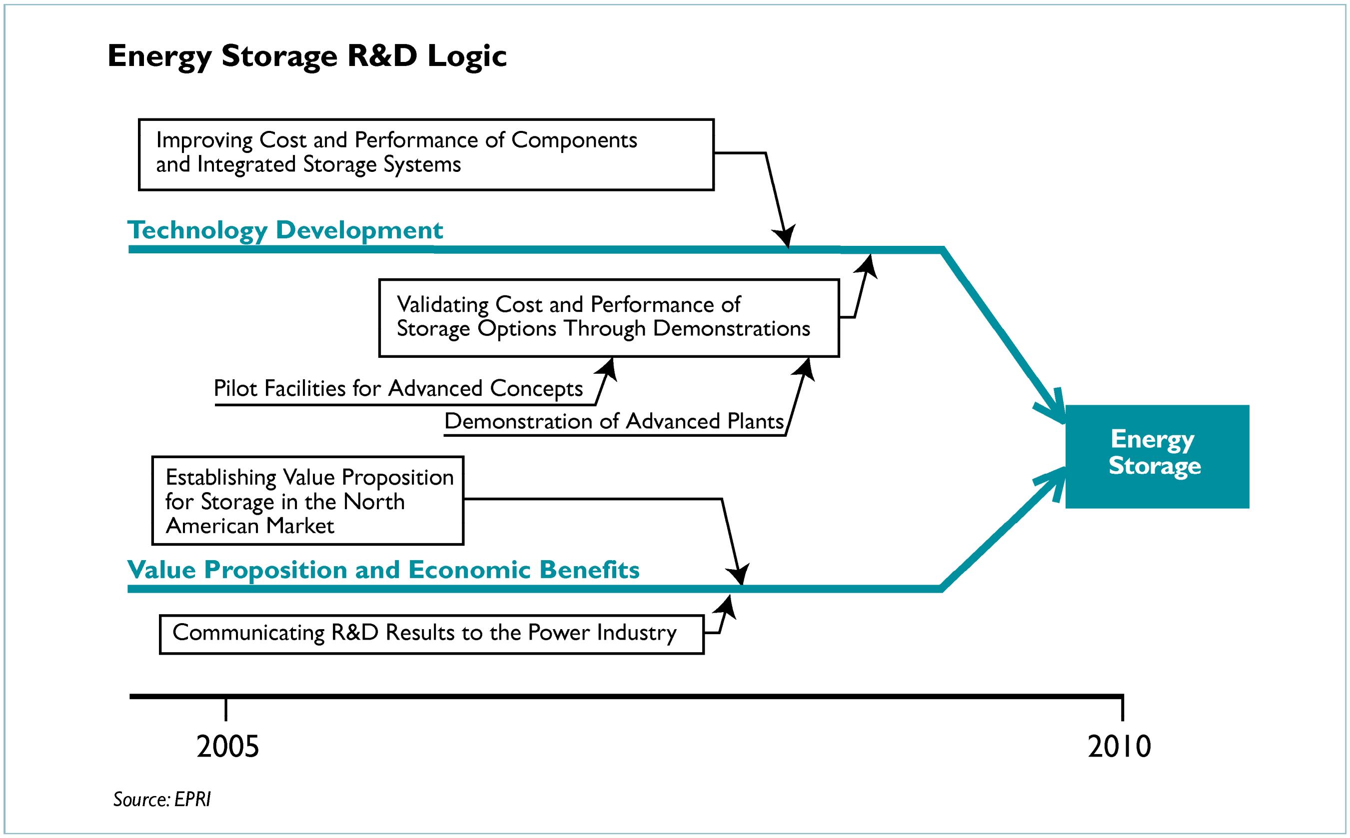


FIGURE 6-7. This chart illustrates key milestones on the road toward improved energy storage and its effective strategic use.

LIMITING

CHALLENGE 5

Transforming Electricity Markets

Today's electricity market faces numerous economic, political, operational, and regulatory challenges. *New financial risk management models* will help policymakers better understand the allocation of risk in complex electricity transactions. *Better transmission grid planning* will ensure adequate investment in new transmission grid technology and transmission grid expansion. *Improved transmission grid management* will enhance the administration of the transmission grid and improve scheduling and dispatch, security, and reliability. *Retail market reforms* will provide new electricity service options and greater market flexibility.

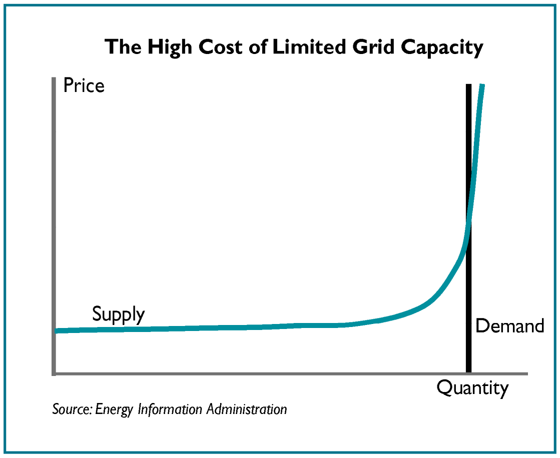


FIGURE 6-8. Failure to address the limitations of today's transmission and distribution systems could produce higher power prices tomorrow.

The Need for Transforming Today's Electricity Markets

Over the past three decades, the U.S. electricity industry has been shaped by two oil embargoes, high rates of inflation in the early 1980s, new and more stringent emissions limitations, and evolving debates on global climate change and the role of nuclear power in the world's electricity generation portfolio. More recently, federal- and state-level deregulation schemes have transformed the industry, which is still struggling to establish stable and transparent electricity markets that provide adequate power supplies and margins and the improved quality needed to accelerate productivity and competitiveness. The ultimate goal of deregulation is to ensure open and transparent markets for all participants as well as a robust infrastructure free of operational, security, and service vulnerabilities.

One of the biggest challenges associated with implementing deregulation is creating a regulatory framework that will ensure accountability for the development, operation, and maintenance of the electricity network infrastructure. New regulatory models should reward investment and innovation and incorporate incentive mechanisms to resolve energy/environmental tradeoffs, such as carbon emissions. These models should also address the large discrepancies in financial risk borne by various players in the electricity market. On the operational level, more research is needed to determine the best organizational forms, governance, and incentives for improving transmission system reliability. In addition, new operating standards could allow transmission operators to optimize the allocation of transmission resources and respond rapidly to substantial, real-time deviations from day-ahead schedules.

The development and enhancement of emerging T&D technologies will also be necessary to reduce the cost and improve the responsiveness of the national power grid. For example, Flexible AC Transmission Systems (FACTS) could enable power delivery systems to respond more quickly to changing conditions and thus foster further development of wholesale markets. Other technologies, such as real-time metering and communication/control options, will be needed to enable electricity suppliers and service companies to more quickly develop new service offerings, differentiate electricity products, and unbundle retail services.

Emerging Solutions

In today's transitional market, wholesale electricity prices may fluctuate greatly while "legacy" regulatory frameworks may include retail price caps and other features that do not support sustainable competition. Because these "built-in" inefficiencies place a disproportionate share of financial risk onto electricity suppliers, addressing market risk allocation is a high priority. Sustained research is required to (1) compare and analyze successes and failures of the various "experiments" with restructuring conducted in recent years, (2) synthesize a sequential plan for restructuring that minimizes the overall risk of systemic failures, and (3) develop new regulatory provisions that efficiently allocate risk in the industry, with special attention to ensuring the financial solvency of default service providers. Another critical task is coordinating investments in new transmission technologies and expanding the capability of the transmission grid with the addition of new generating capacity. Unlike many countries, the U.S. has no existing national system for coordinating investments in fuels, generation, transmission, and related factors essential to the infrastructure of energy industries. Finally, improving transmission grid administration is important to increasing system-wide flexibility, which, in turn, is critical to enabling new power service options and rapid response to changes in demand.

Funding Requirements

R&D initiatives necessary for developing and deploying new market designs and related technologies will require approximately $150 million per year over the next 10 years.

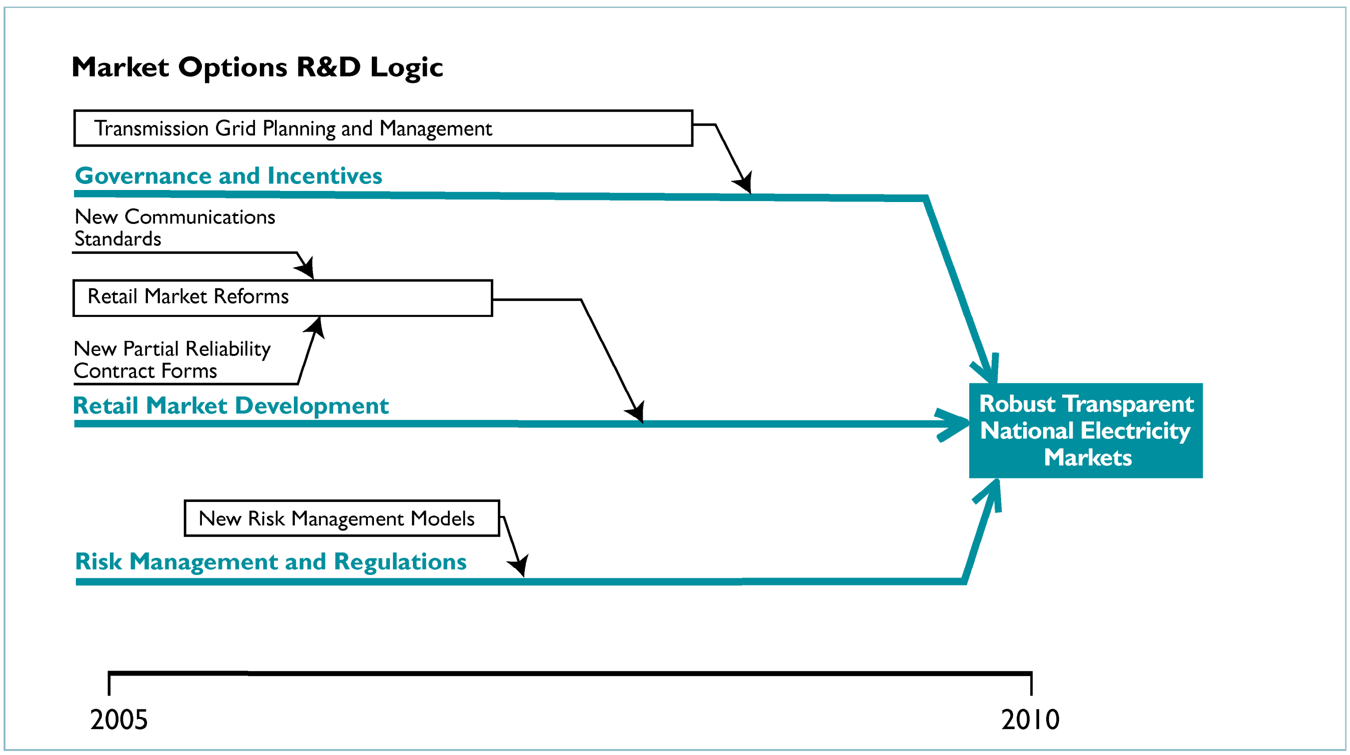


FIGURE 6-9. This chart illustrates key milestones on the road toward robust and transparent electricity markets.

MOST CRITICAL R&D NEEDS:
For Transforming Electricity Markets

Retail Market Reforms

- *Critical needs:* Demand response enabled by advanced customer "portals" and real-time pricing; flexible service contracts that provide incentives for energy conservation and a variety of payment options; a comprehensive database of wholesale electricity prices; sophisticated models for forecasting electricity market behavior
- *Approach:* Collection of market data and pricing models; an analysis of current retail pricing policies; close collaboration between regulators and energy industry organizations

New Financial Risk Management Models

- *Critical needs:* A research program designed to efficiently and equitably allocate financial risk throughout wholesale and retail electricity markets as well as across generation, transmission, and distribution sectors
- *Approach:* A thorough analysis of the financial solvency of default electricity providers; the development of sophisticated market simulation tools

Transmission Grid Planning

- *Critical needs:* Development of novel mechanisms to coordinate investments in transmission and generation infrastructure, such as independent transmission companies (for-profit firms that own and operate the transmission system, as in the U.K. and several other countries) and the non-profit independent system operator
- *Approach:* Research considering the potential viability of for-profit independent transmission companies versus management by non-profit entities, such as ISOs and RTOs; the development of innovative methodologies for forecasting future demand

Transmission Grid Management

- *Critical needs:* A report comparing the efficiency of existing designs of reserve markets; a comprehensive scheme for evaluating both supply-side and demand-side reserves in terms of quality attributes, such as response time or ramp rate; a report comparing two-part bids for reserved capacity and called energy; designs of day-ahead procurement auctions and a comparison of their predicted efficiency with alternative approaches via either (a) day-ahead optimization or (b) long-term contracts and options; new performance-based incentives designed to reward transmission operators for efficient service; new organizational structures designed to optimize transmission flexibility and responsiveness
- *Approach:* Analysis of current scheduling/dispatch practices, strengths, and weaknesses; the simulation of promising approaches

LIMITING

CHALLENGE 6

Electricity-Based Transportation Systems

Electric vehicles are an environmentally friendly alternative to conventional cars that promise to reduce U.S. dependence on imported petroleum. *New electricity storage systems* will improve the fuel efficiency of plug-in hybrid gasoline-electric vehicles. *Fuel cell-battery hybrid vehicles* will provide further gains in efficiency (and environmental benefits) as well as lower vehicle costs. *Advanced on-board charging systems* will provide greater operational flexibility for a wide spectrum of electric vehicles. And *mobile distributed generation technologies* will enable battery-powered electric-drive vehicles to supplement existing electricity generation resources.

The Need for Electric Transportation

The U.S. transportation sector must reduce its dependence on petroleum. Over 96% of the total energy used in transportation comes from petroleum, representing energy consumption of over 13 million barrels of oil per day. About 55% of that is imported. If this pattern continues, petroleum consumption will grow to 19 million barrels of oil per day by the year 2020, with 62% imported. In addition, the emission of greenhouse gases from transportation sources could grow by as much as 50% over this time period, from approximately 500 million metric tons carbon equivalent to over 750 metric tons. For consumers, the transportation industry's dependence on petroleum means driving will become ever more costly as gasoline prices increase. One possible solution to the American transportation dilemma is the broad substitution of electric vehicles for conventional gasoline-powered cars and trucks. However, this will require a complete transformation of U.S. car and truck markets that, in turn, poses considerable technical and market-driven challenges. These include increasing the range of grid-dependent battery electric vehicles (BEV), enhancing the efficiency of hybrid electric vehicles (HEV), and raising consumer awareness of electric vehicle benefits.

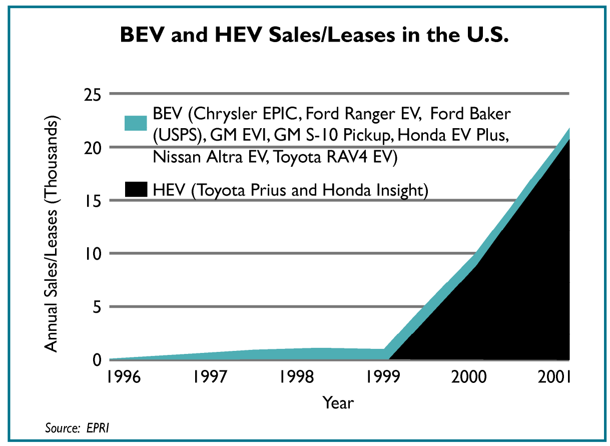


FIGURE 6-10.

Sales of hybrid electric vehicles (HEV) have increased dramatically over the past few years, fueled by the introduction of hybrid editions of familiar makes and models.

Emerging Solutions

To date, the electric vehicles with the most mass-market appeal have been grid-independent hybrid gasoline-electric vehicles. These vehicles have a battery pack small enough that cost is not prohibitive, yet they also deliver significant fuel savings. Additional research and development is necessary to improve upon existing hybrid designs to give owners the option of plugging in at night, thereby reducing trips to the gas station. Enhancements include larger battery storage systems and low-cost fuel cells. In addition, on-board charging systems could offer greater operational flexibility for battery-optional hybrids as well as battery-only cars and utility vehicles. And, as electric vehicles of all kinds become more popular, they could also offer supplemental electricity as the ultimate distributed generation resource.

Funding Requirements

Strong public/private partnerships would provide financial and technical support for building and testing proof-of-concept integrated systems and key components. Upon satisfactory evaluation of the proof-of-concept vehicles, prototype vehicles and small fleets will be built and tested as part of national value analysis. To accomplish this, approximately $200 million per year is required over the next 10 years. This funding does not include the auto industry's large vehicle development program.

MOST CRITICAL R&D NEEDS:
For Electric Transportation

Fuel Cell Battery-Powered Hybrid Electric Vehicles

- *Critical needs:* Fuel cell batteries compatible with plug-in hybrid electric vehicle designs; proof-of-concept fuel cell-powered hybrid vehicles
- *Approach:* Technical and cost data for major subsystem components, particularly the fuel cell itself; advanced models capable of analyzing performance, life, and cost characteristics of fuel cell designs; new hybrid vehicles designed for optimal performance with fuel cells

Electricity Storage Batteries

- *Critical needs:* Nickel metal hydride (NiMH) and lithium-ion (Li-ion) plug-in hybrid electric vehicle batteries that offer greater storage capacity and lower manufacturing costs than existing options
- *Approach:* Testing state-of-the-art NiMH and Li-ion batteries to determine best life capacity; identification of issues that limit deep cycle life; improvements in battery operation and control, design, and materials to extend battery life

Mobile Distributed Generation

- *Critical needs:* Infrastructure enabling electric-drive vehicles to provide power services to grid operators as well as emergency and/or uninterruptible power supply services to electricity users
- *Approach:* A detailed examination of complex issues surrounding the connection of electric-drive vehicles with the existing power grid

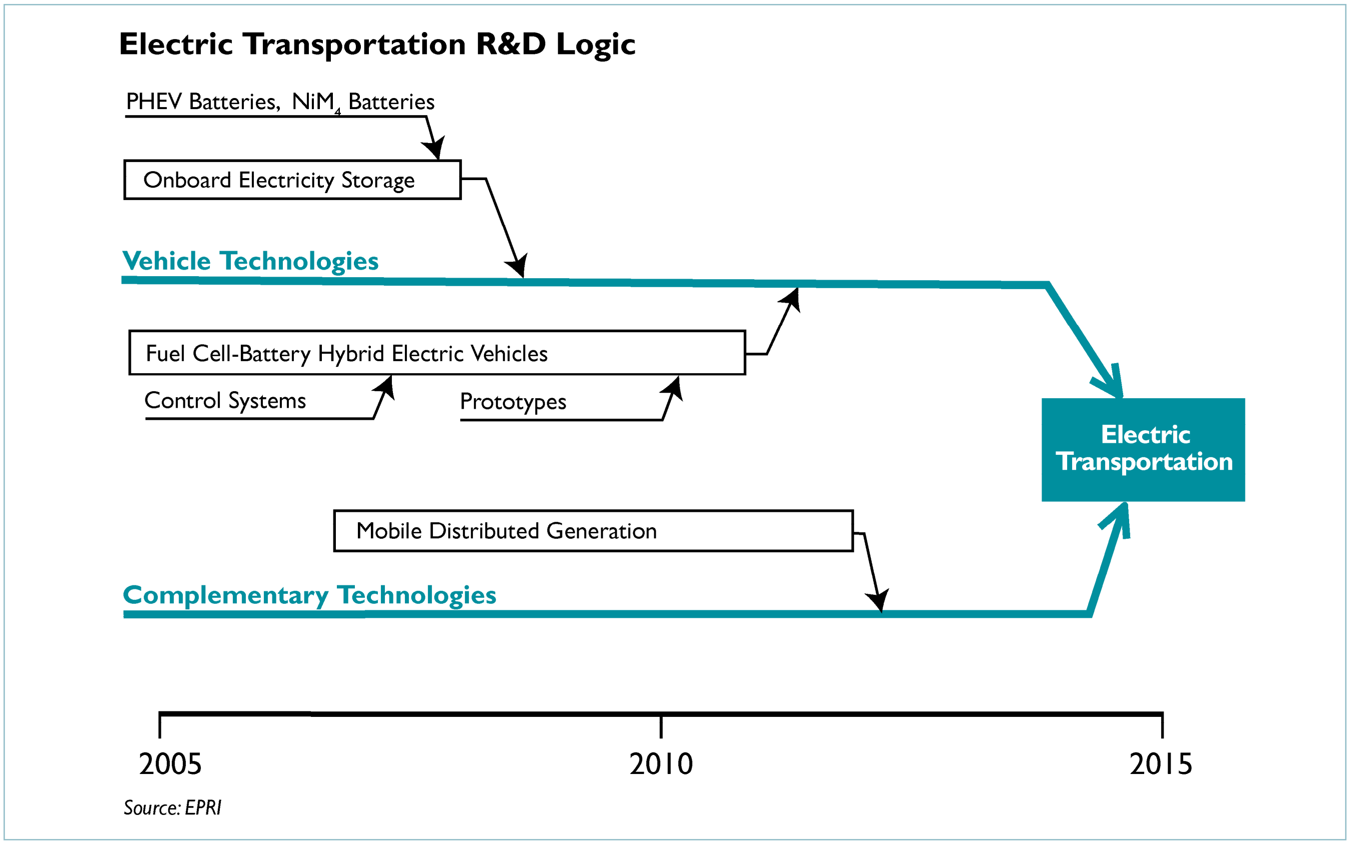


FIGURE 6-11. This chart illustrates key milestones on the road toward cost-effective and marketable electric transportation systems.

LIMITING

CHALLENGE 7

High-Efficiency End Uses of Electricity

Technology innovations can radically increase productivity, reduce energy intensity, minimize waste streams, enhance quality of life, and improve business practices, combining to ensure robust economic growth. *Industrial electrotechnologies* could improve product quality and reduce energy use while generating less waste. *New light sources* may offer substantial energy savings to virtually all end-use sectors. *Indoor environment* improvements could deliver significant health and productivity benefits. Improvements in information technology, focusing on data centers, connectivity, energy efficiency, and functionality will provide continued increases in economic productivity. *Automating the recycling of electronics* will recapture key resources, and encouragement of *industrial ecology* can multiply all such gains.

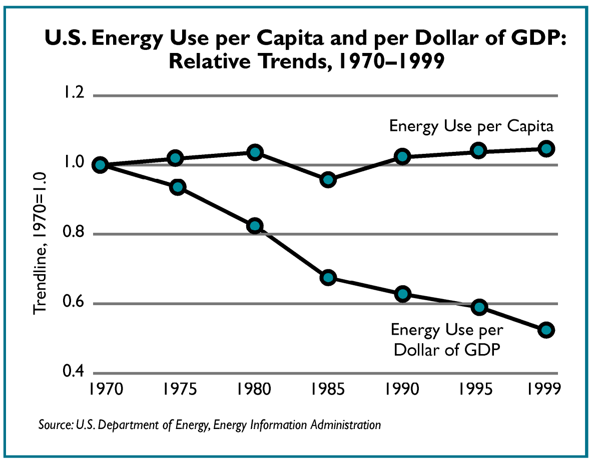


FIGURE 6-12. More efficient end-use technologies contribute to productivity gains.

Tomorrow's Need for Innovative End-Use Technologies

Electrification is one of the most important inventions of all time. It made possible a string of innovations that included the internal combustion engine, chemicals and pharmaceuticals, and electronic entertainment and communication. With innovation and economic growth, simultaneous improvements in energy efficiency and productivity are possible. Improving industrial processes and indoor work environments, reducing waste, purifying air and water, and improving human performance can all be accomplished more efficiently while increasing individual and overall productivity and GDP. During most of the 20th century, productivity per U.S. employee grew steadily. Information technology has played a major part in fueling economic growth and prosperity since the mid-1990s. In recent years (1985–2000), U.S. energy intensity (energy per dollar GDP) declined at compound energy-savings rates of almost 1.5% per year.

Maintaining such progress over the next 50 years, however, will be a challenge. Experience has shown that it takes a string of breakthrough technologies (not just one, such as information technology) to sustain high growth rates in productivity. And, while the fast growth of electronics and information technology has produced new economic opportunities, it has also created environmental problems, such as the rapid accumulation of obsolete electronic equipment and associated scarce or hazardous materials in landfills due to the high cost of recycling. Moreover, key U.S. industry sectors face continuing competition from foreign producers, stringent environmental compliance requirements, and high labor costs.

Emerging Solutions

Improvements in end-use technology—over both the short and long term—can help the U.S. economy continue to grow at a sustainable rate. For example, market transformation efforts to increase market penetration of existing energy-efficient motors, drives, and power supplies could occur in the next few years. Likewise, pilot projects and field demonstrations to assess, validate, and document the performance of existing and emerging products—such as membranes for cleaning landfill gas, freeze concentration processes for separation and purification, and microwave processes for chemical synthesis, curing, and water purification—could be completed within two to five years.

Technology and product development efforts to provide high-efficiency products where they do not exist, such as advanced light sources and consumer appliances, will require up to 10 years or more. Emerging industrial electrotechnology innovations, such as nanotechnologies, microwave-driven synthesis, electrochemical catalysis, electro-separation, and biotechnologies, promise to dramatically reduce labor costs and improve efficiency. For example, in food processing, electro-separation could replace today's costly distillation, leading to more food at lower cost. Ultra-efficient light sources could slash lighting costs for all uses, and new techniques for improving the indoor environment promise to improve both productivity and health. Automated disassembly could make electronics recycling a new, profitable industry. And eventually "industrial ecology" could link the energy and materials streams of many different uses to minimize waste, effort, and cost, improving efficiency and productivity even more.

The application of new technologies to improving the efficiency of office equipment—which accounts for about 2% of U.S. electricity use—continues to exhibit rapid growth. Currently, semiconductor and computer manufacturers are leading the way to produce faster and cheaper equipment. Similarly, in the computer monitor area, efforts to improve displays with organic light emitting diodes and advanced liquid crystal displays are ongoing.

To facilitate the rapid development of new technologies, a "model" Internet Data Center (IDC) is recommended that could serve as a template to showcase the best design concepts and best technology. This model IDC would also serve as a vehicle to increase cooperation and develop an ongoing dialogue between developers and electricity providers.

Funding Requirements

R&D initiatives described in Limiting Challenge 7 need $600 million per year over the next 10 years.

MOST CRITICAL R&D NEEDS:
For High-Efficiency End Uses of Electricity

Industrial Electrotechnologies

- *Critical needs:* Designing, developing, and demonstrating commercial applications of freeze concentration processes for solid/water separation in food processing and waste processing; microwave processes for ethylene production, dehydration of food, chemical and ceramic curing, and waste treatment; polymer-based membranes for producing usable fuels from landfill gas; and advanced oxidation processes for controlling air pollutants
- *Approach:* Partnership with public agencies, such as DOE, and industry to develop and commercialize key industrial technologies

Advanced Light Sources

- *Critical needs:* Identifying, developing, testing, and commercializing new fluorescent light sources with efficacy (efficiency) of 200 lumens/watt; new phosphor materials that emit two visible photons rather than one; high-intensity discharge (HID) light sources with twice the efficacy of current HIDs; improved incandescents; and solid-state lighting
- *Approach:* Collaborative support of R&D by federal and state agencies, national laboratories, other researchers, and major lamp manufacturers

High-Efficiency Motors, Drives, and Power Supplies

- *Critical needs:* Developing and commercializing low-cost, high-performance electric motors, drives, power supplies, and other critical components of electric-drive vehicles
- *Approach:* R&D to enhance existing technologies and develop cost-effective manufacturing processes

Indoor Air Quality (IAQ) and Productivity

- *Critical needs:* Enhancing air quality using advanced technologies, including dilution (ventilation), capture (filtration), destruction, and source removal; addressing technical issues pertaining to controlling pathogens, tobacco smoke, humidity, and volatile organic compounds
- *Approach:* Establishing a clear quantified relationship between enhanced indoor environment and improved productivity; expanding R&D to develop and enhance IAQ technologies; laboratory tests of new IAQ technologies; large-scale demonstrations, related data collection, and subsequent information dissemination and commercialization

Automating Electronic Equipment Recycling Processes

- *Critical needs:* Developing efficient disassembly and extraction processes for common types of electronic equipment; automating these processes
- *Approach:* R&D to develop, test, and enhance standard “production line” disassembly processes; partnerships with manufacturers and recycling companies to test, refine, and automate these processes

LIMITING

CHALLENGE 8

Advances in Enabling Technologies

R&D programs aimed at achieving technological breakthroughs require a longer time horizon and a broader focus than those dedicated to incremental improvements. Enabling technologies such as *biotechnology*, *smart materials*, *nanotechnology*, *fullerenes*, *information technology*, and *sensors*, will be the basis for new limit-breaking improvements, transforming electricity and other key technical underpinnings of modern society.

Enabling technologies are those that fundamentally change industry, business, or quality of life—often by making other technology breakthroughs possible. In modern times, the most important enabling technology undoubtedly has been electrification. Widespread electrification has enabled the development of countless other breakthrough technologies, including radio and television, telecommunications, industrial automation, and modern computing. Finding, developing, and exploring such technologies, however, presents considerable R&D challenges. Unlike research that seeks modest improvements in existing technologies, R&D programs that focus on enabling technologies often involve cutting-edge scientific inquiry across a broad range of technical disciplines. This crosscutting aspect of the research promotes synergy and increases opportunities for true technological breakthrough. The work, by its nature, covers a long time horizon and involves a relatively high level of research risk.

Today, areas that show particular potential as enabling technologies include biotechnology, smart materials, nanotechnology, fullerenes, information technology, and sensors; research in any one of these fields could produce the next transformational technology.

Emerging Solutions

While it is difficult to divine the future of any research endeavor, it is especially hard to foresee the result and value of the more cutting-edge technologies. For example, early computer scientists, when asked in the 1950s what they were working on, said "a machine for making numerical calculations much more quickly." There was absolutely no idea that, decades later, computers would constitute a technology platform with a central role in nearly every aspect of our lives, from manufacturing and commerce to communications, transportation, and entertainment. Today, areas that show particular potential as enabling technologies include biotechnology, smart materials, nanotechnology, fullerenes, information technology, and sensors; research in any one of these fields could produce the next transformational technology.

Biotechnologies promise efficient new techniques for toxic waste cleanup, and biomimetic materials—man-made materials that mimic the behavior of organic materials—appear to have a wide variety of applications. *Smart materials* (which can sense and physically respond to changes in their environment) and molecular-scale *nanotechnologies* could dramatically change approaches to modern engineering and process design. *Fullerenes*—a type of carbon molecule with unequalled strength, toughness, and both metallic and semiconducting electrical properties—could essentially revolutionize materials science. And advances in *information technology* and *sensors* will support the practical application of virtually all other technology R&D.

MOST CRITICAL R&D NEEDS:
For Advances in Enabling Technologies

Smart Materials

- *Future possibilities:* Real-time condition assessment of critical components; control of power plant chemistry; combustion and emissions control; avoidance of sub-synchronous resonance; increased transmission line capacity
- *Approach/technology needs:* Effective integration of discrete smart-system sensors, actuators, and processors; miniaturization of smart components to allow embedding in structures; wireless communication with embedded components

Nanotechnology

- *Future possibilities:* Customized medication-delivery vehicles; stronger, tougher composite materials; more efficient industrial catalysts; inexpensive polymer nanorod photovoltaic cells; molecular-scale electronic circuits
- *Approach/technology needs:* Development of nanoscale fabrication processes; advanced self-assembly techniques; greater understanding of quantum effects; communication links with nanoscale structures

Fullerenes

- *Future possibilities:* Super-strong, lightweight structural materials; carbon nanotubes; cable with electrical conductivity more than 10 times greater than copper; nanoscale machines and electronic devices
- *Approach/technology needs:* Reliable, low-cost production of fullerenes in industrial quantities; nanotube handling and fabrication techniques; high-strength bonds with matrix substances

Biotechnology and Biomimesis

- *Future possibilities:* High-strength, protein-based adhesives; self-assembled, low-cost photovoltaics; advanced fuel cells based on proton pumping across cellular membranes; ethanol-based alternatives to petroleum feedstocks; photo-induced decomposition of water
- *Approach/technology needs:* Better understanding of basic biological processes and mechanisms; light harvesting techniques that mimic photosynthesis; research into ion transport in plants; development of enzyme-like catalysts

Information Technology

- *Future possibilities:* Enhancements in man-machine interfaces; automated control of dynamic processes; virtual-reality-based training systems; information security systems; data mining
- *Approach/technology needs:* Advancements in neural networks, fuzzy logic, genetic algorithms, intelligent agents, and artificial intelligence

Sensors

- *Future possibilities:* High-accuracy sensors for power plant digital control systems; specialized sensors for chemical species and high-temperature environments; real-time measurement of emissions and waste streams; microsensors for voltage and current; distributed temperature measurement in transformer windings
- *Approach/technology needs:* Development of acoustic wave detectors and electrochemical microsensors; increased temperature resistance of optical fibers, sensor housings, claddings, coatings, and adhesives; development of low-cost, versatile fiber Bragg gratings; microminiaturization of sensor components

A Glimpse of the Future

In many cases, a number of these developments could be combined to produce an efficient, robust solution to a real-world problem—for instance, avoiding the catastrophic failure of a gas or steam turbine. In this case, distributed nanoscale strain sensors, fabricated from smart materials through a biomimetic process, might be embedded into the rotating machinery in such a way that would not upset the machine's dynamic balance. Advanced information technology algorithms could then be used to mine the resulting real-time operating data, predict incipient failure, signal the need for maintenance, and alter equipment operation to prevent an immediate failure event.

Other high-value possibilities include low-cost photovoltaics that use biomimetic self-assembly of nanoscale materials; high-strength, high-conductivity transmission lines consisting of fullerenes fabricated biomimetically; and advanced sensors and smart materials technology for distributed temperature measurement and maximization of throughput in power lines.

Funding Requirements

R&D initiatives necessary for developing the next generation of enabling technologies will require $1 billion per year over the next 10 years.

LIMITING CHALLENGE 9

Strengthened Portfolio of Generation Options

A broad portfolio of generation options is critical to ensuring enough reasonably priced electricity to support economic growth, quality of life aspirations, and environmental protection. *Fossil fuel generation options that facilitate emissions capture or produce no emissions* make the best use of existing fuel resources. *Renewable energy options* coupled with robust storage options address the intermittent nature of most renewable fuels. Next-generation *nuclear power plant technologies* offer safety and operational improvements as well as zero emissions. *Distributed energy resources (DER) technologies* enhance power system flexibility.

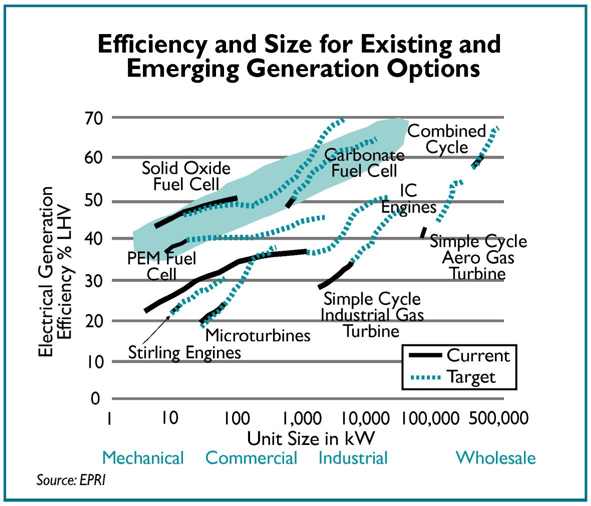


FIGURE 6-13.

New generation technologies must address both small- and large-scale production needs.

Need for Fuel Diversity

A diverse fuel portfolio offers strategic flexibility in the face of future uncertainty and the economic advantage of fuel competition. But the current U.S. and global generation portfolios are determined by current economic, environmental, and political realities, which often promote a narrow set of generation options with even more restricted fuel choices.

In the near term, most new and projected U.S. power plants will use natural gas for both environmental and economic reasons. However, the price of natural gas can fluctuate dramatically with availability, which could produce higher electricity prices. Moreover, gas prices are likely to both increase and become more volatile as the U.S. energy economy grows more dependent on natural gas-fired plants.

At the same time, environmental concerns may lead to reductions in allowable CO_2 emissions for U.S. plants. Depending on the cost of carbon capture and storage technologies, these restrictions could require the closure of numerous coal-fired plants, resulting in a corresponding need for the public to accept higher electricity prices. With such future scenarios, a more diverse set of future generation options is urgent.

Emerging Solutions

To adequately address fuel supply uncertainty, price volatility, energy security, and global sustainability, the global electricity portfolio should consist of a broad range of energy sources, including fossil, renewables and hydro, and nuclear power.

Highly efficient fossil generation system designs that maximize emission capture from the energy conversion process can help keep costs down and minimize emissions per unit of electricity production. Advanced coal technologies—such as ultrasupercritical (USC) and integrated gasification combined-cycle (IGCC) plants—are particularly important because they can make coal—a cheap, widely accessible fuel—competitive under stringent emission reduction scenarios.

Renewable resources—such as the wind, sun, and biomass—are virtually inexhaustible and generally allow the production of pollution-free energy. In addition, incorporating renewable energy sources and nuclear energy into the generation portfolio helps manage the risks associated with fossil-fuel price fluctuations. Renewable energy (including new, low environmental impact hydropower) technologies can also be built in small capacity increments proportionate to load patterns and local need, using locally available fuel sources to allow individual regions, states, and nations to become more energy self-sufficient and sustainable.

An aggressive program to lower CO_2 emissions must include nuclear power alternatives. The current fleet of nuclear power plants makes major contributions to U.S. efforts to reduce fossil fuel emissions and improve air quality. CO_2 emissions avoided through the use of nuclear energy equals the amount of CO_2 generated by about 135 million cars (about two thirds of the total), or roughly 40% of the total currently emitted by all U.S. coal plants.

Over the short term, different types of distributed energy resources may offer greater generation flexibility and help certain customers obtain greater power reliability and quality.

Over the long term, advanced hydrogen fuel cells as well as renewable solar and wind power solutions could support a zero-emissions option for distributed resources. On a larger scale, they may provide a clean and cost-effective foundation for the electrification of developing countries. Novel, hydrogen-based power cycles that offer high performance at low or no emissions could also support sustainable electrification.

Funding Requirements

R&D initiatives necessary for enhancing existing generation options and developing new ones will require an estimated $2.3 billion per year over the next 10 years.

MOST CRITICAL R&D NEEDS:
For Maintaining and Strengthening the Portfolio of Generation Options

Efficient, Low-Emission Options for Fossil Fuel Generation

- *Critical needs:* Low-NO_X solutions, enhanced gas turbines, and improved reliability, availability, and maintainability (RAM) for natural gas-fired plants; advanced coal-fired plant designs, including integrated gasification combined-cycle and ultrasupercritical plants; advanced CO_2 capture options for conventional coal-fired plants
- *Approach:* Utilities to host technology demonstrations; development of long-term R&D plan

Maintaining and Improving Nuclear Power Options

- *Critical needs:* Technologies that address reliability issues for boiling water reactor (BWR) and pressurized water reactor (PWR) primary systems and other key plant components; new designs and effective processes for cost-effective light water reactor deployments; technology basis for safe helium reactor
- *Approach:* The application of reliability-focused technologies to resolve issues and manage assets; medium-term R&D for economic high-performance standardized ALWRs and for demonstration of stable licensing processes; long-term R&D for advanced designs; working with regulators/others to optimize safety of new designs

The Application of Hydrogen as an Energy Carrier

- *Critical needs:* Advancing hydrogen production, delivery, storage, conversion, and safety
- *Approach:* Long-term R&D plan; developing proof-of-concept systems; recruiting utilities to host demos

Improvements in Renewable Energy Performance to Improve Commercial Value

- *Critical needs:* Low-cost, high-efficiency photovoltaic systems with goals of $1,000 per kW and 35% efficiency; reduced cost of biomass gasification; improve the efficiency and reduce the cost of renewable hydrogen production
- *Approach:* Continued development of Si and post-Si devices and long-term field tests; the development and demonstration of multi-fuel gasification concepts and wood waste demos; the identification of novel concepts for hydrogen production

Addressing Intermittency Issues Associated with Renewable Power Generation

- *Critical needs:* Combining intermittent generation (IG) sources with storage devices; improving the electric grid's ability to accept IG; short-term forecasting to predict IG output
- *Approach:* Investigating/testing new storage technologies; developing intelligent models and control schemes to integrate intermittent sources with grid; researching wind forecasting methods

Improving the Cost and Efficiency of Fuel Cells and Other DER Options

- *Critical needs:* Increasing solid oxide fuel cycle (SOFC) power density; reducing the cost of a manufactured SOFC stack to under $100/kW; extending SOFC life to more than 100,000 hours with less than 0.1% voltage degradation per 1,000 hours; lower non-fuel O&M costs to less than 0.5 cents/kWh; developing flexible microturbines and gas turbines suitable for integration with the SOFC
- *Approach:* Defining specifications for hybrid systems and demonstrate prototypes; develop most promising fuel cell components; partnering with organizations associated with the DOE's SECA program

Additional Critical Capability Gaps

- Sustaining the Current Fleet of Fossil and Nuclear Generation Plants During Transition to Advanced Technologies
- Novel Power Cycle Concepts to Minimize Emissions and Maximize Fuel Flexibility

Power Generation in the Roadmap

Work associated with this Limiting Challenge supports the following Roadmap objectives:

1. Providing electricity at reasonable costs to support economic growth, health, and well-being in both developed and developing countries
2. Protecting the environment both in terms of local and regional air/land/water issues and with respect to global climate to resolve the energy/carbon conflict
3. Contributing to an ultimate goal of global sustainability in terms of the energy resources needed for electricity supply

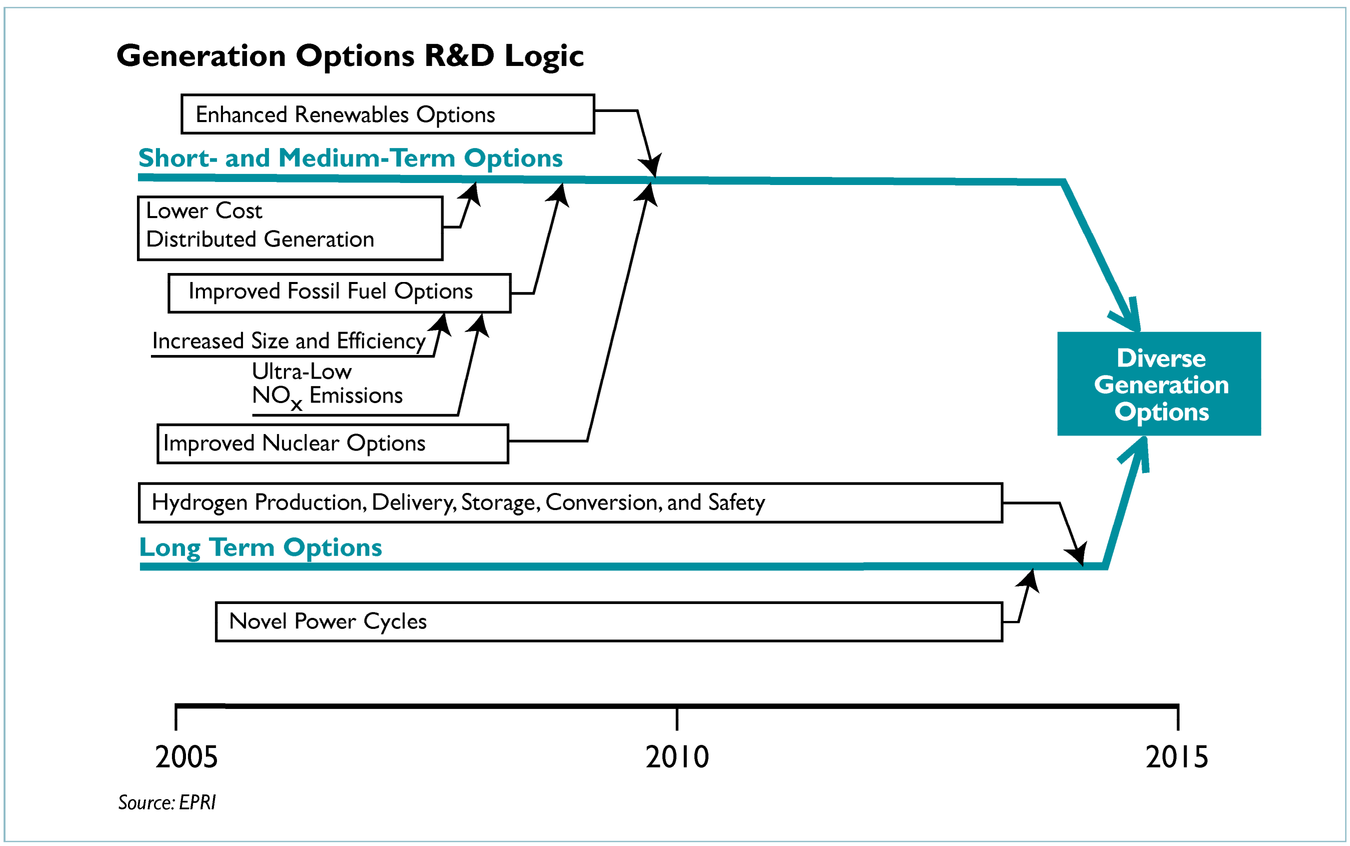


FIGURE 6-14. This chart illustrates key milestones on the road toward a robust electricity generation portfolio.

LIMITING
CHALLENGE 10
Universal Global Electrification

Global access to reliable, affordable electricity is essential to ensuring economic growth, protecting environmental assets, and improving public health. *Innovative power infrastructure technologies* will reduce the costs of electrification and offer reliability and power quality benefits. New *financing mechanisms* will make electrification projects more attractive to private organizations (as well as international agencies) by improving profitability and reducing risk. Research that quantifies the many *economic and social benefits* of universal electrification will support national, regional, and local energy policymaking.

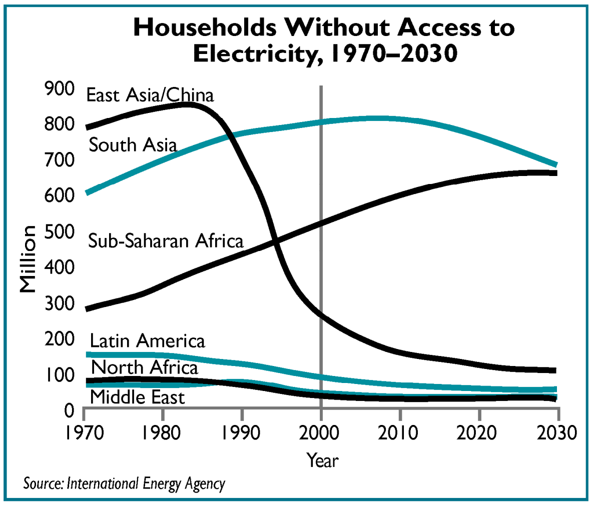


FIGURE 6-15. Under business-as-usual conditions, large segments of the world population will remain without electricity.

The Global Electrification Challenge

Approximately 1.6 billion people—one quarter of the world's population—have no access to electricity. An additional 800 million have very limited access to electricity. Most of these people are among the over 2.8 billion who survive on less than two dollars a day and face inordinately high risks of disease, starvation, homelessness, and exploitation. Even as we face the challenge of promoting sustainable development for these people, the world's population is expected to rise another 3 billion by 2050. Access to a basic level of electricity and related services could offer dramatic improvements in the quality of life for the world's poorest populations—contributing, in part, to potential gains in health, education, and economic opportunity. But the challenge is daunting. The least electrified corners of the world are beset by unstable governing bodies and often poorly managed economic systems; in extreme cases, corruption or inefficient management may deter investors and siphon scarce resources away from intended electrification and related projects. Even in countries where a stable government and policy infrastructure exists, many much-needed electrification projects do not offer sufficient return-on-investment to make them attractive to investors.

Emerging Solutions

The answer to the global electrification question will require a combination of innovative new policies, finance mechanisms, and infrastructure technology. Work is urgently needed to improve the current knowledge base on the prospects for global electrification, particularly with respect to varying national, regional, and local conditions and needs. This knowledge base will provide a solid foundation for the creation of new institutional structures—including markets—that will, in turn, create regulatory frameworks for the efficient delivery and sale of electricity. That knowledge will also support the development and application of financing mechanisms, including microfinance and electricity cooperatives that can reduce risks and improve returns for small and large private investors. Another high priority is R&D that will facilitate development of more cost-effective power infrastructures that are suitable for serving these loads, including generation, transmission, and distribution systems in addition to communications and control systems.

Funding Requirements

R&D initiatives necessary for universal electrification will require approximately $400 million per year over the next 10 years.

MOST CRITICAL R&D NEEDS:
For Achieving Universal Global Electrification

Financing of Electrification Projects

- *Critical needs:* Flexible electricity pricing and demand forecast models; improved understanding of why some electrification projects (in South Africa and China) succeeded
- *Approach:* Researchers to collect data on past electrification projects; analysts to leverage existing financial models to interpret data; medium-term R&D plan

Power System Infrastructure—Generation, Transmission, and Distribution

- *Critical needs:* The identification of least-cost/best-performance technologies for regional electrification strategies; the development of more cost-effective (and easy to manufacture) generation, transmission, distribution, and storage technologies
- *Approach:* Focus on key performance characteristics (reliability, availability, maintainability, and durability); long-term R&D plan involving utilities as well as regional organizations

Role of Electrification in Economic Growth

- *Critical needs:* Short- and long-term electrification goals applicable at the national, regional, and local levels; an improved understanding of the relationship between electrification and economic growth; an improved understanding of the relationship between electricity and other energy sources
- *Approach:* Researchers to collect and combine existing information on grid extension, cooperatives, and other electrification programs; analysis of collected information; an assessment of additional research needs

Additional Critical Capability Gaps

- Electric End-Use Technologies—Needs include energy-efficient water desalination and purification technologies
- Environmental Issues—Carbon management strategies are key

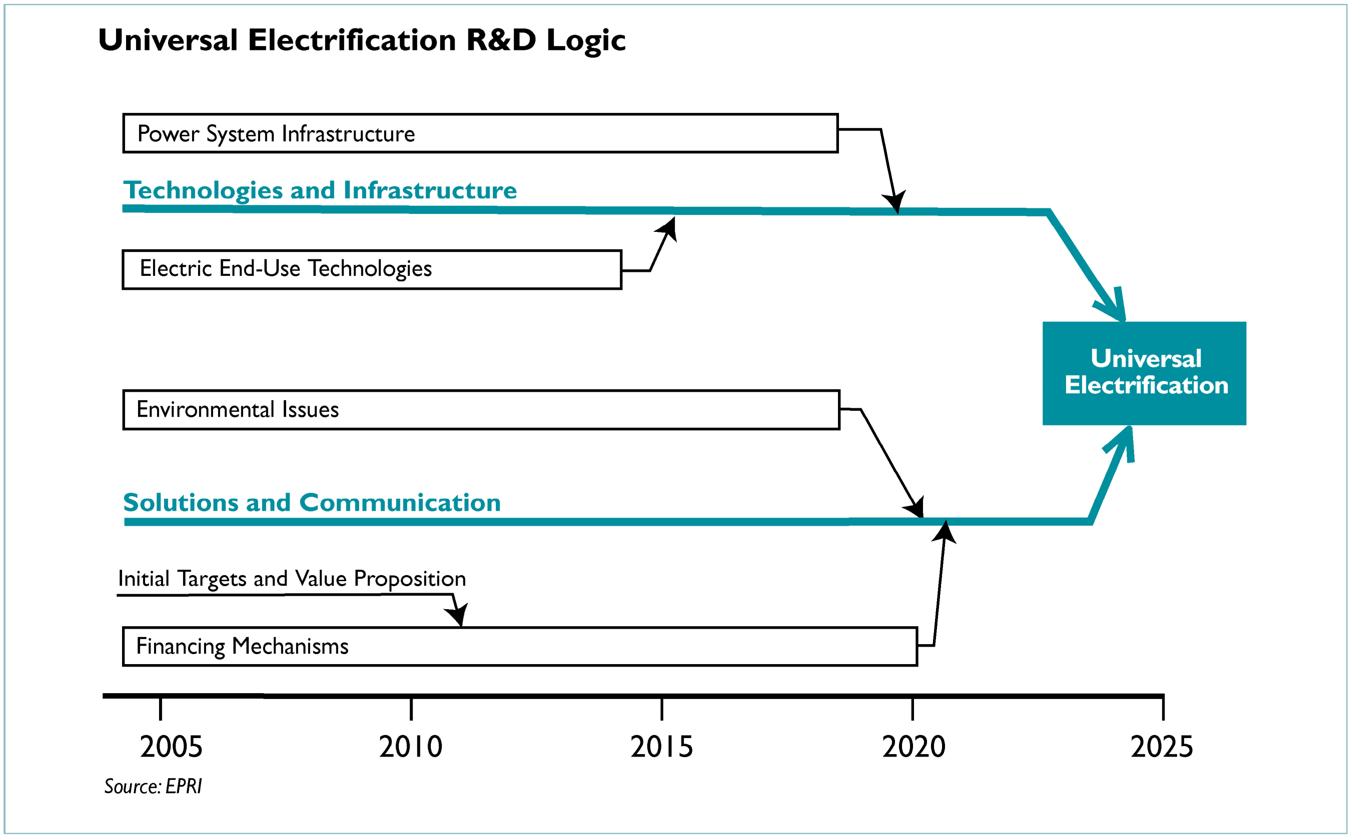


FIGURE 6-16. This chart illustrates key milestones on the road toward universal global electrification.

LIMITING CHALLENGE 11

Carbon Capture and Storage Technologies

Economical technologies for sequestering carbon dioxide (CO_2) need to be developed if fossil fuels are to remain as environmentally acceptable, affordable energy sources for electricity production. This was considered to be the most critical Limiting Challenge in the suite of issues needed to address carbon management. These technologies may include direct methods of capturing CO_2 from the combustion process and depositing it into geologic formations, as well as indirect methods such as managing forests to maximize the amount of CO_2 removed from the atmosphere through photosynthesis. An accelerated program of research, development, and demonstration is needed in order to realize the benefits of carbon capture and sequestration technologies within the next few decades.

Carbon Dioxide Issues Overview

Fossil fuels—primarily coal, oil, and natural gas—account for nearly 80% of the world's primary energy consumption. While driving the engine of global economic growth and prosperity, fossil fuel combustion also creates CO_2, the predominant greenhouse gas. By the dawn of the 21st century, CO_2 emissions associated with human activity had grown to more than $6x10^9$ metric tons, or 6 gigatons, of carbon per year, and the concentration of CO_2 in the atmosphere had risen from 280 parts per million by volume (ppmv) in pre-industrial times to about 370 ppmv.

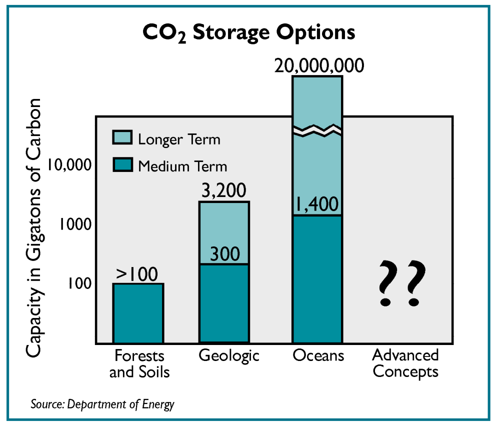


FIGURE 6-17. New storage options are needed to curb increasing concentrations of atmospheric CO_2.

Continued growth in energy demand—especially in developing countries—is projected to further increase global emissions of CO_2 and its atmospheric concentration. This trend conflicts with the scientific consensus that stabilizing the atmospheric concentration of CO_2 and other greenhouse gases is necessary to avoid adverse effects on the world's climates. Ultimately, fossil fuel combustion will have to be displaced by electricity and hydrogen from low- or zero-carbon emitting sources. Full-scale development of many of these technologies, however, will take several decades. In the meantime, affordable methods for reducing the net addition of CO_2 to the atmosphere must be developed if growth in the atmospheric concentration of CO_2 is to be curbed. The use of existing renewable and nuclear technologies to accelerate this process is discussed under Limiting Challenge 9. In contrast, no technology is, at present, commercially available for capturing and disposing of CO_2 from power plants. Adapting the process used for food-grade CO_2 production appears to be energy intensive and costly; applying it to a power plant could nearly double the cost of electricity and leaves the unanswered question: where will we put the captured CO_2?

R&D Costs and Funding Mechanisms

R&D initiatives for the development of carbon sequestration technologies will require at least $300 million per year over the next 10 years.

MOST CRITICAL R&D NEEDS:
For CO_2 Capture and Storage

Advanced Concepts R&D

- *Critical needs:* Collaborative process to generate breakthrough approaches to CO_2 capture
- *Approach:* Incentives for public/private idea-generation efforts; also R&D consortia

Pilot- and Full-Scale Demonstrations of Direct Sequestration

- *Critical needs:* Real-world data on candidate technologies in power plant conditions; assurance of full-scale success of technologies for varied fuels and situations
- *Approach:* 5–10 integrated pilot facilities worldwide; full-scale follow-ons to pilot plants; coordination with new power systems R&D; public/private funding

Regulatory, Legal, and Societal Issues

- *Critical needs:* Regulatory/liability solutions; assurance of acceptability to public
- *Approach:* Studies of precedents; action framework; long-term public education campaign

Carbon Disposal Stability

- *Critical needs*: Proof of geologic and ocean sink stability; ocean fertilization effects
- *Approach:* Lab testing on basics; measurement methods; test data; predictive models

Additional Critical Capability Gaps

- Methods for Assessing Investment Decision Options
- Assessment of Health/Ecological Risks

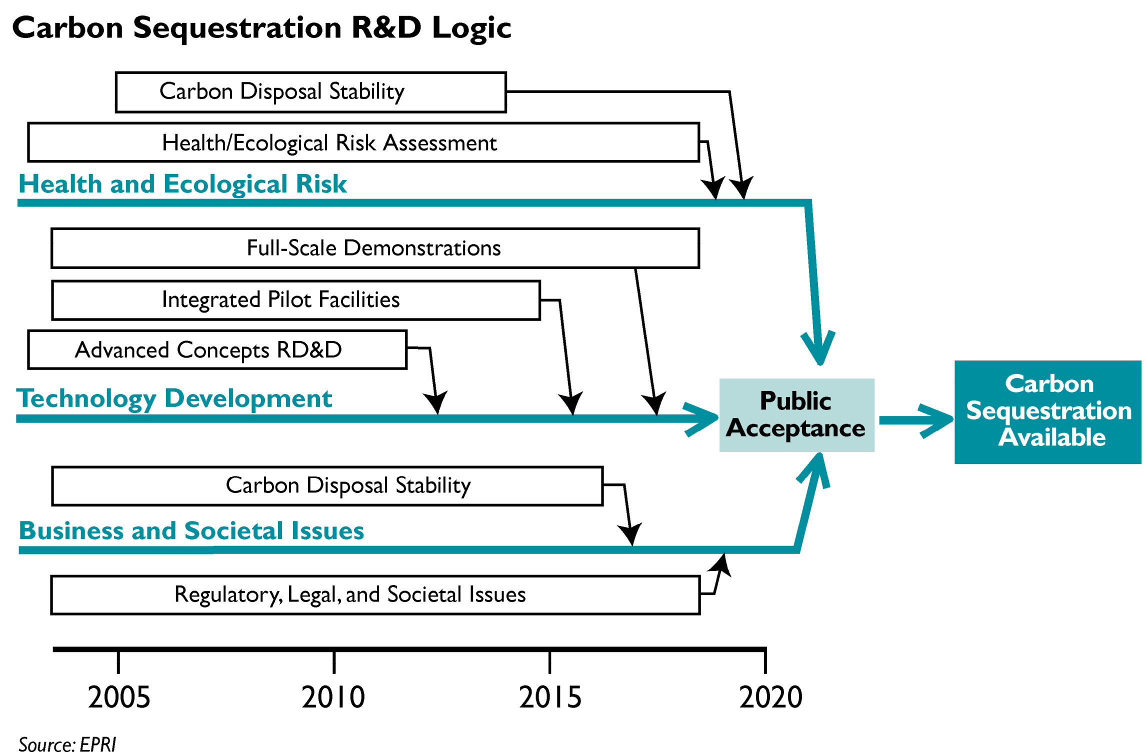


FIGURE 6-18. This chart illustrates key milestones on the road to carbon sequestration.

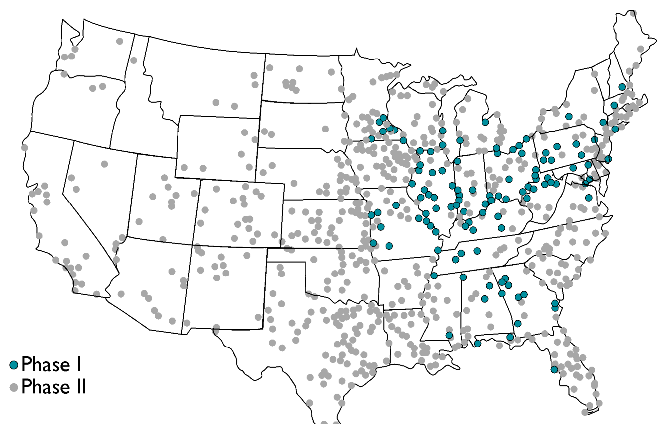
LIMITING

CHALLENGE 12

Ecological Asset Management

Market-based management frameworks that account for the economic value of natural capital (i.e., "eco-assets") promise to help address the challenges of eco-asset management and achieve environmental goals more efficiently and at lower cost. *Institutional frameworks and standardized policies* will support the design of efficient rules-based markets. *Studies and demonstrations* will enable the development of multiple markets specializing in different eco-asset commodities and different scales (i.e., local, regional, and international). Innovative software tools and strategies will allow companies and large landowners to maximize the value of the eco-assets and adopt long-term eco-asset-based strategies.

The Expanding U.S. Acid Rain Emissions Trading Program



Source: Environmental Protection Agency

FIGURE 6-19. Market-based programs can be a very effective way of mobilizing industry to rapidly achieve environmental goals.

The Need for a New Approach to Environmental Regulation

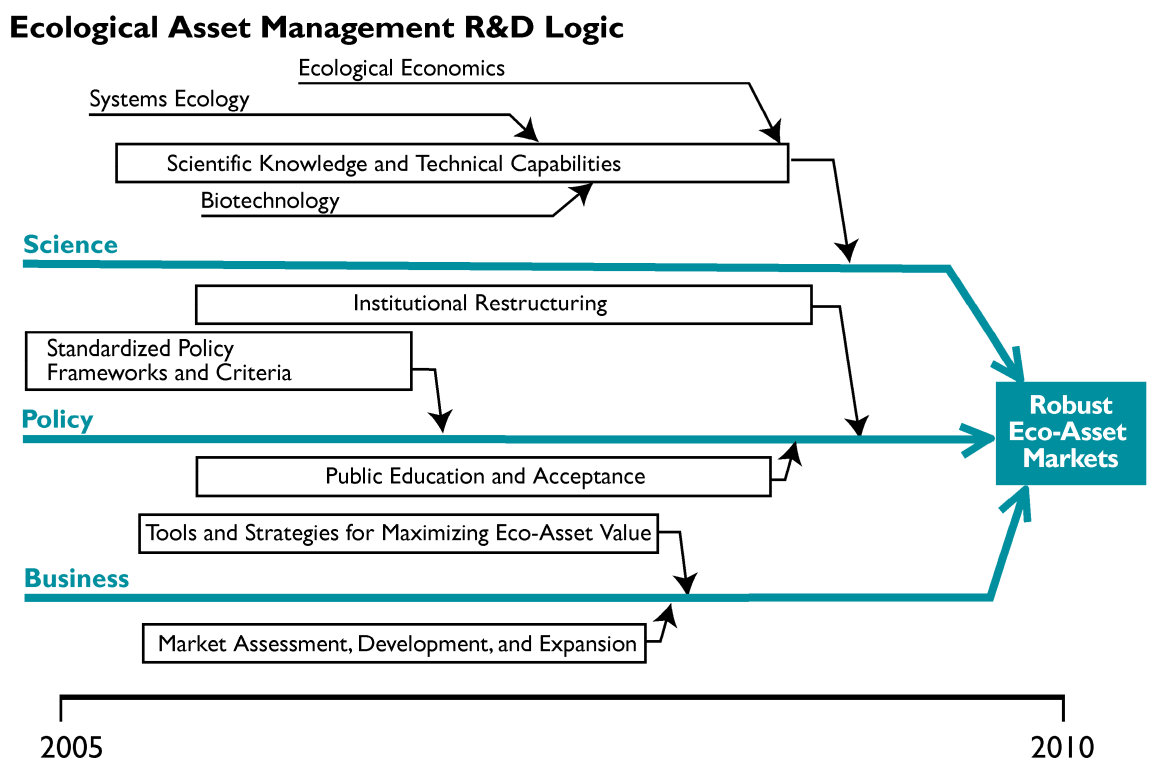
Over the past 30–40 years, command and control regulations (i.e., those that operate without using market mechanisms) have significantly improved environmental protection and clean up. However, many public and private sector experts believe that augmenting command and control rules with market-based approaches can improve the cost-effectiveness of environmental regulations and accelerate environmental gains. One of the most effective market-based approaches to environmental control is the "cap and trade" concept. In the cap and trade concept, regulators set a maximum limit (i.e., a cap) for emissions of a particular pollutant in a given geographical area. Marketable permits are established among regulated entities that can then be traded and sold while maintaining the overall emissions cap. This concept was incorporated into federal environmental policy through the passage of The Clean Air Amendments of 1990, which established a trading system for sulfur dioxide and nitrogen oxides. The success of these programs showed that market-based approaches, when implemented effectively, improve environmental outcomes at lower cost. Similar thinking can be applied to other environmental issues, in which the preservation and enhancement of natural resources have real economic value.

Emerging Markets

In recent years, environmental markets have begun to emerge, grow, and diversify. These markets essentially assign a dollar value to the services ("eco-assets") provided by both natural and managed ecosystems. Policymakers and regulators are helping to create these markets by establishing incentive-based environmental management frameworks that reward investments for eco-asset preservation, enhancement, restoration, and creation. In addition to SO_2 and NO_X emissions allowances, commodities such as aquifer recharge credits, wasteload allocations for point and nonpoint source pollutants, and mitigation credits for wetlands, biodiversity (critical habitats and listed species), and riparian buffer zones are being bought and sold in U.S. markets. For other commodities—notably, emission offset credits for carbon dioxide and other greenhouse gases—markets are emerging over scales ranging from regional to global.

Funding Requirements

At least $50 million per year over the next 10 years is needed to ensure continued progress toward the development of robust eco-asset markets.



Source: EPRI

FIGURE 6-20. This chart illustrates key milestones on the road toward robust eco-asset management options.

MOST CRITICAL R&D NEEDS:
For Ecological Asset Market Development

Tools and Strategies for Maximizing Eco-Asset Value

- *Critical needs:* Resource management and business strategies for the informed, effective design and implementation of organization-level eco-asset frameworks
- *Approach:* Developing algorithms to model environmental processes, assess risks, evaluate the impacts of market-based management options, etc.

Public Education and Acceptance

- *Critical needs:* Comprehensive educational programs aimed at the financial community and the general public
- *Approach:* Meetings with stakeholders to identify key issues; press briefings; the development of press kits and online media

Market Assessment, Development, and Expansion

- *Critical needs:* The development of city, state, regional, national, international, and global markets for a variety of eco-asset-based commodities and derivative instruments
- *Approach:* Studies and demonstration projects focused on existing and emerging eco-asset markets (such as those for credits associated with wetlands, biodiversity, and terrestrial carbon sequestration)

Institutional Restructuring and Standardized Policy Frameworks

- *Critical needs:* The development of laws, regulations, and guidelines applicable to eco-asset-based financial instruments; the standardization of laws and regulations across various levels of government
- *Approach:* Facilitating dialogue amongst all key stakeholders; analyzing gaps in existing regulatory and oversight frameworks; the training of eco-asset specialists within relevant agencies

Additional Critical Capability Gaps

- Scientific Knowledge and Technical Capability

LIMITING

CHALLENGE 13

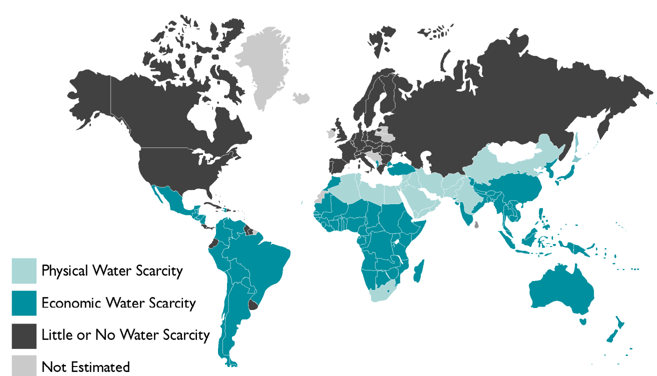
Improving Water Availability and Quality

Universal access to affordable electricity and clean water is essential to sustainable economic growth and related health and environmental benefits. But addressing tomorrow's water and electricity requirements will be a complex challenge, involving numerous stakeholders; interconnected ecological, legal, technical, and financial issues; and security concerns. *Advanced modeling techniques* will allow coordinated resource policymaking at the watershed level. *Innovative water management technologies* will enable power plants, industrial facilities, and communities to meet economic development and environmental goals.

Water Issues Overview

Assuring water availability, quality, and security in an environmentally acceptable manner is essential to ensuring sustainable economic growth and improving public health. Nonetheless, key stakeholders in both developed and rapidly developing countries are currently facing serious water management challenges. The emerging watershed approach to enhancing water management requires balancing the needs of multiple stakeholders residing in multiple legal jurisdictions, and developing optimal water allocation, stream flow, land use, and other policies that foster appropriate growth in electricity demand and supply. At the same time, increasingly stringent environmental regulations—formulated at the global, national, and local levels—mean that both public agencies and private businesses, through public/private partnerships, must join forces to solve water issues at both the macroscale and microscale levels.

The Coming Water Scarcity Challenge, 2025



Source: International Water Management Institute

FIGURE 6-21. Improving access to clean water is another key component of a sustainable global economy. By 2025, much of the world will face some degree of water scarcity.

Emerging Solutions

Improving the supply, utilization, and security of water in any given area is a complex undertaking that depends on an integrated understanding of the infrastructure for water and electricity; land use; commercial, industrial, residential, and agricultural practices; habitat and indigenous species; environmental regulations; and climate change issues. At the "macro" (watershed) level, this challenge can be addressed by enhancing models that simulate how these numerous factors interact. With the accurate forecasts and "what-if" analyses created by these models, stakeholders will be able to set better water allocation and discharge targets. At the "micro" (community or industrial facility) level, public and private facilities will need cost-effective technologies to meet their water resource management responsibilities as determined by macroscale policies. Critical infrastructure providers, such as electric utilities and water treatment agencies, will have added security responsibilities.

Funding Requirements

R&D initiatives necessary to improve water availability, quality, and security will require at least $100 million per year over the next decade in the U. S. alone. Further funding—perhaps hundreds of millions of dollars—will be required to perform demonstrations of the technologies developed and to address international issues. Because of the tremendous size and scope of these projects, their success will depend on public/private partnerships, potentially catalyzed by EPRI and other international research institutions with strong ties to both sectors.

MOST CRITICAL R&D NEEDS:
For Improving Water Availability, Quality, and Security

Prioritizing Opportunities for Water Management—U.S. and International

- *Critical needs:* The identification and prioritization of communities for which water availability, quality, and/or security issues will be most important to economic growth, public health, and environmental quality over the next decades
- *Approach:* Partnership with global, national, and regional organizations to obtain and analyze key data and to develop forecasting methodologies; public/private funding

Creating Robust Ecological, Hydrological, and Water Allocation Models

- *Critical needs:* Collaborative processes to (1) understand relationships between human and environmental water uses within a watershed, (2) extend existing water management models and water allocation decision processes, and (3) build new models and decision-making processes where needed
- *Approach:* Enhancing and validating existing models based on new applications; developing new models; developing consensus decision processes; public/private funding

Developing Water Production, Recycling, Conservation, and Security Technologies

- *Critical needs:* R&D aimed at the development and initial testing of new technologies; commercialization of most promising emerging technologies
- *Approach:* Public/private partnerships involving water and electricity industries, government agencies and R&D laboratories, manufacturers, universities, and others

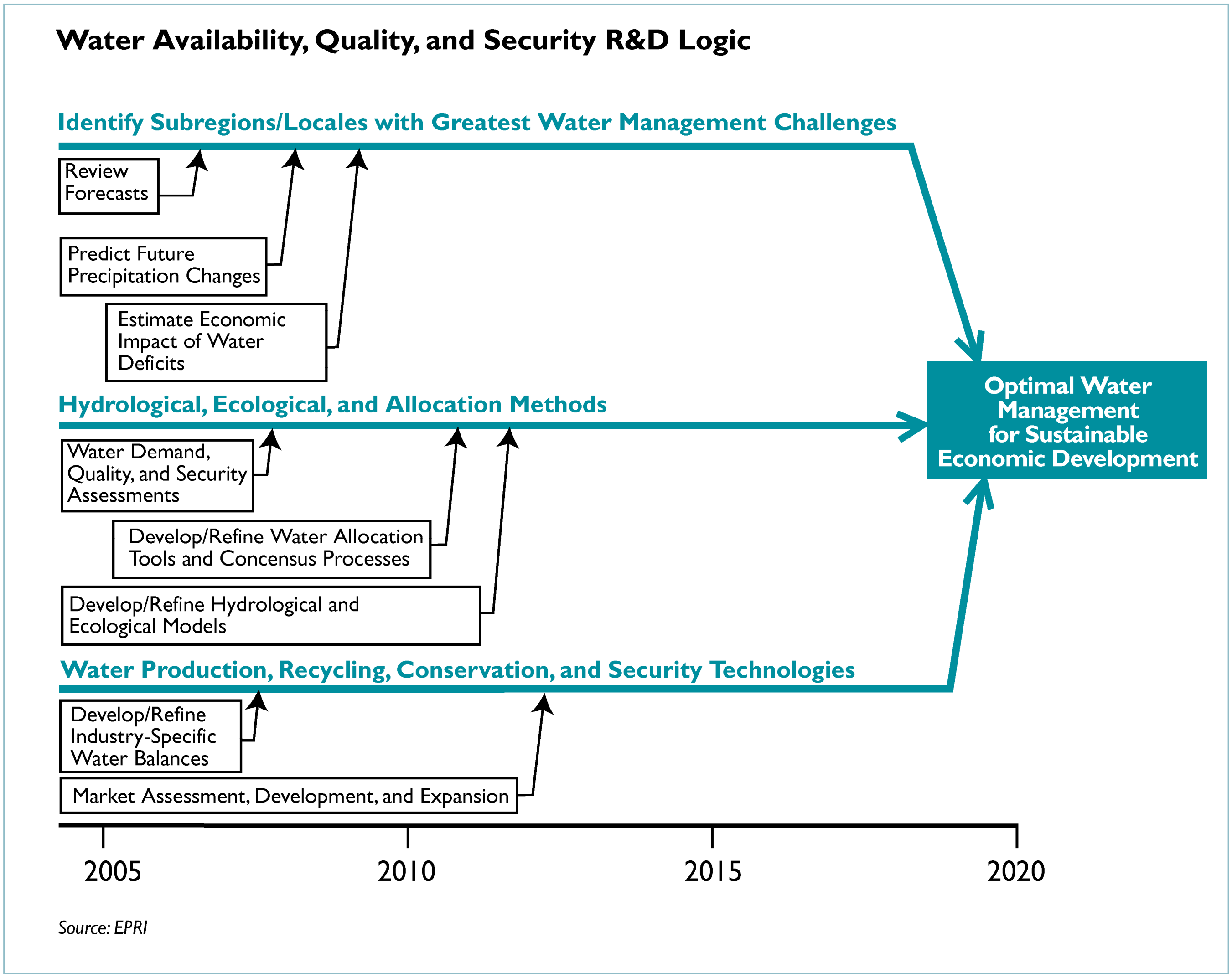


FIGURE 6-22. This chart illustrates key milestones on the road toward improved water quality, security, reliability, and availability.

LIMITING

CHALLENGE 14

Environmental Science

More fundamental research is necessary to improve our understanding of the environmental risks and benefits associated with electricity generation and use. This information is critical to those in the electricity business, policymakers who influence technology choices and assess risks, and the public, which is both a consumer of electricity and part of the global environmental fabric. The most critical issues needing further research are: *the health impacts of air pollutants*, such as fine particulates and toxics (e.g., mercury); the role of electricity generation and use in *climate change*; the importance of *water availability and quality for development*, including electricity generation; whether *electric and magnetic fields* from T&D lines lead to adverse health effects; and how to best manage the *wastes and useful products* (e.g., fly ash, heat, wood poles, contaminated soils) associated with electricity generation and use.

These environmental issues and others will be particularly important as the electricity enterprise evolves to deploy *new generation technologies* such as distributed energy resources (DER), integrated gasification combined-cycle (IGCC) with carbon capture and sequestration, advanced nuclear power, renewables such as photovoltaics, and hydrogen-based energy technologies, such as fuel cells. Two key approaches are likely to greatly influence how environmental issues are managed in the future—*risk assessment/life-cycle analyses* and *market-based rulemaking*. Both of these approaches will be integral to achieving global sustainability through development and use of clean, advanced electric power systems.

To effectively address the issue of CO_2 and other greenhouse gas emissions, it is critical that the underlying science be well understood, that policy options are well framed and examined, and that the rules for managing greenhouse gases are well designed and implemented.

Tomorrow's Environmental Science Needs

In this century, global demand for electricity will rapidly increase, driven by such powerful forces as population growth, urbanization, expanding global commerce, and the imperative to improve quality of life. It is estimated that 10,000 GW of new generation capacity will be needed globally over the next 50 years. From an environmental and health perspective, this is good news, because societies that derive a greater portion of their energy from electricity have both greater economic output (and thereby are able to provide better healthcare) and lower emissions per unit of energy consumed.

Nevertheless, there are significant environmental issues associated with electricity generation and delivery, and these issues will become even more important as the world adds generation and delivery capacity. Most coal-fired power plants emit gaseous pollutants, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_X), particulates and trace elements (such as mercury), and carbon dioxide (CO_2). They also use large quantities of water and generate wastes. Operation of the power delivery infrastructure also has environmental impacts: it produces electric and magnetic fields, uses millions of wood poles treated with preservatives, and can interfere with electronic communications and bird migration.

One of the world's greatest environmental challenges is managing global climate change. Unlike many other environmental concerns, it is truly global in scope and requires global action for its ultimate resolution. To effectively address the issue of CO_2 and other greenhouse gas emissions, it is critical that the underlying science be well understood, that policy options are well framed and examined, and that the rules for managing greenhouse gases are well designed and implemented.

The human and environmental impacts of fine particulate matter and other air pollutants have been examined for decades, but we have only recently begun to understand the actual causative agents and physiological mechanisms involved. Using epidemiology, toxicology, and exposure assessment, together with sophisticated monitoring systems, we are getting closer to identifying the specific components of the particles in our air that are most responsible for observed health effects. Similarly, taking a total ecosystem approach to the examination of emission sources, transport mechanisms, geophysical cycling, and toxicology of substances such as mercury, we are able to more effectively determine not only biological and ecological impacts, but also which management strategies would most benefit society.

Electric power generation and delivery creates products and wastes that must be effectively managed. Materials such as fly ash from coal combustion, which have many established commercial uses (e.g., cement substitution in concrete), may change in character with new environmental controls and require changes in management strategies. Wood poles used in the electric distribution system must be properly disposed of, or used in safe commercial applications, as they contain regulated preservatives. Finally, electric T&D systems generate low-level electric and magnetic fields, which continue to be scrutinized in relation to effects such as childhood leukemia and various forms of cancer.

Future electricity generation and delivery options will all have environmental uncertainties and potential consequences that must be addressed. The goal will be to identify and resolve these issues and potential impacts at an early stage of technology development, making it possible to minimize potentially significant impacts in the technology design phase, rather than after deployment. Risk assessment and life-cycle analyses will be critical to placing environmental consequences in perspective. They will also help provide additional information to assess total costs (including environmental externalities) and public acceptance.

Emerging Solutions

Managing the environmental impacts of global electricity generation and delivery requires solid scientific, technological, and economic information. Using the best scientific information available reduces uncertainty and allows decision makers to most cost-effectively address and mitigate the problems that pose the greatest risk to the public and to the environment. It is likely that risk assessment methodologies will be refined to more effectively define levels of exposure that provide adequate margins of safety for human and environmental protection. This will be particularly relevant for coal-based environmental issues, which present some of the most vexing challenges for the future. Because coal is the world's most abundant fossil fuel, with hundreds of years of available reserves, it is imperative that ways be found to use coal in an environmentally sustainable way.

Air Quality and Human Health

One of the critical areas where scientific research can play a pivotal role is providing a better understanding of which constituents in ambient air contribute to adverse health effects. This allows policymakers to focus on controlling emissions from those sources that most contribute to these effects, thus resulting in more effective policies for protecting public health. A prime example today is fine particulate matter (PM) from fossil fuel combustion, which has been shown to be associated with negative health effects. However, fine PM is composed of many organic and inorganic compounds. Recent research is finding that the carbonaceous fraction is the most toxic, not sulfates or nitrates (the predominant component of PM). Thus, controlling sulfates and nitrates may not result in any positive health benefit. Likewise, more work is necessary to determine how mercury from power plants and other sources contributes to human exposure through fish consumption, and whether some compounds, such as arsenic, actually have thresholds below which no adverse effects occur.

Global Climate Change

As discussed previously in the Roadmap, society is moving forward with policies aimed at stabilizing greenhouse gas concentrations, but the target concentration levels have not been determined. Thus, it is critically important to understand the implications of climate policies and measures, how the climate system works, the impacts of climate change, how we might adapt to—and benefit from—climate changes, and what technology options and strategies will be needed to mitigate undesirable climate change. Research to date has shown that to stabilize greenhouse gas concentrations at levels that will not negatively interfere with human societies and ecosystems, we will need to make major investments in technological advances to produce and consume energy in ways that emit far less greenhouse gas emissions per unit of GDP than is the case today. Greater electrification is crucial to success in this endeavor.

Electric and Magnetic Fields

There is an ongoing need to address the potential health effects from exposure to EMF. This is especially true as we build new power lines (for new customers and those not currently served) and improve the existing infrastructure. Research institutions, such as the California Department of Health Services, and others abroad have cited the apparent relationship between magnetic fields and childhood leukemia as a cause for concern. Other studies have associated EMF exposures to cardiovascular disease and cancer. Research is needed to address these issues as we expand the global infrastructure to deliver electricity to its ultimate markets. One emerging hypothesis regarding the potential link between childhood leukemia and magnetic fields is “contact current” (e.g., touching a metallic surface with a low electrical potential, causing a small current to flow through the child’s body, including the bone marrow, that reaches ground via another conductive medium such as the drain in a filled bathtub).

Wastes and Useful Products

The production and delivery of electricity generate significant amounts of wastes as well as products with commercial value. It is important that wastes are minimized, are non-hazardous in nature, and can be reused or recycled in some way. For example, fly ash from coal combustion is increasingly being used in commercial applications such as highway and building construction. A large quantity of combustion products is landfilled worldwide and must be managed to protect ground and surface water. This becomes particularly important as new control technologies are deployed on power plants to remove mercury, which will then become part of the solids being used commercially or placed in landfills. Wood poles containing preservatives can potentially impact surrounding soils; these power poles must be managed once their useful life is over, perhaps in another application.

Water Use

Almost every large electricity generating station uses water, either for cooling (thermo-electric) or for driving turbines (hydroelectric). Increasing competition for this precious resource will constrain its future use for power generation. Thus, the electricity enterprise must be involved in defining multiple approaches to resolve freshwater availability challenges. For example, greatly improved integration of electricity production and water use, treatment, and recycling will help communities reduce water consumption and provide essential services at lower cost. Further, water supports not only human life, but also aquatic ecosystems that must be protected and enhanced. Thus, there will be a need for an improved basis to develop and implement standards to protect water quality cost-effectively. Finally, as new technologies are deployed for future electricity generation or to remove pollutants from existing power plants, emissions from such technologies must be properly characterized and potentially treated.

Emerging Environmental Issues and Management Strategies

Many of the issues noted above are being addressed today, but still require additional research—at an accelerated pace—to meet societal environmental objectives in the most cost-effective manner. However, new issues are also likely to emerge such as potential impacts of hydrogen transport and use or whether stored carbon dioxide can permanently remain in saline aquifers or other geological repositories. Large-scale deployment of distributed generation technologies such as microturbines may have unanticipated air quality, noise, or EMF impacts compared with central-station generation and transmission/distribution to consumers. Wide-scale application of renewables, such as wind, biomass and solar, may have land-use impacts or change local microclimates. A unifying theme for the future of environmental issues and the electricity enterprise is sustainability. An entire section of the Roadmap is dedicated to this issue.

Funding Requirements

At least $900 million per year over the next 10 years is needed to ensure sufficient research to address critical environmental science issues.

MOST CRITICAL R&D NEEDS:
For Environmental Challenges of Powering Tomorrow's Global Economy

Human Health and the Environment

- *Critical needs:* Resolving major issues related to particulate matter formation, including secondary organic aerosols; applying epidemiology, toxicology, and exposure assessments through comprehensive studies to focus on components of greatest health risk for control; developing greater understanding of dose-response relationships for toxic compounds such as mercury and arsenic to determine safe levels for human exposure; improving risk assessment methodologies to determine what substances are most critical for reducing exposure and which are less critical
- *Approach:* Expanding methodologies currently being developed to address health effects of fine particulate matter and mercury; employing integrated health risk assessments based on increasingly refined science; collaborating with all stakeholders as part of the process via joint research or public/private partnerships; communicating results to key stakeholders such as the scientific community, industry, regulators, policy-makers, the media, and the public

Global Climate Change

- *Critical needs:*
  - Better understanding of the implications of effective climate change policies, such as tradeoffs among various options, evaluation of economic effects as well as benefits to the global environment, and implications for the electric sector both domestically and internationally
  - Better understanding of how the climate system works and the impacts of climate change, including the extent to which mitigation can reduce potential damages
  - Exploring how adaptation may reduce the impacts of climate change, including options for adaptation, their costs, and identification of the uncertainties involved in the ability of societies to adapt
  - Understanding of how technologies can be deployed most efficiently to reduce greenhouse gas emissions at global, regional, local, and company levels
  - Establishing workable rules and tools for greenhouse gas management, including monitoring progress and emissions trading
  - Developing, demonstrating, and deploying generation and end-use technologies to dramatically reduce greenhouse gas emissions per unit of GDP, with an emphasis on CO_2 capture, transport, and storage technologies, and expanding emission-free nuclear and renewable energy
- *Approach:* Collaboration with all stakeholders via joint research or public/private partnerships; communicating results to key stakeholders such as the scientific community, industry, regulators, policymakers, the media, and the public

Electric and Magnetic Fields

- *Critical needs:*
  - Improving scientific understanding of the association between EMF and childhood leukemia and other health outcomes, which will involve further study of the contact current hypothesis, more laboratory studies of environmental leukemogenesis, and basic research on the interaction between electricity and blood forming components
  - Better understanding of the potential EMF ramifications of the future electricity infrastructure

• *Approach:* Resolving current health concerns such as childhood leukemia through (1) intensive research over the next 5 to 10 years to test the contact current hypothesis, (2) completing a large-scale epidemiology study now underway and determining if others are required, and (3) addressing issues related to the future grid through the assessment of the technologies expected to be applied commercially and the evaluation of whether any potential EMF exposure issues may evolve

Wastes and Useful Products

• *Critical needs:*

– Better understanding of how soils and groundwater may be impacted by waste management practices and operation of existing and planned power generation and delivery systems

– Developing new approaches to cleaning up soils and groundwater in an economical and environmentally benign manner (e.g., via biotechnologies)

– Considering, from the facility design phase, how products from electricity generation and delivery can be effectively recycled or reused, including finding new uses for existing products (such as fly ash, scrubber products, IGCC solids)

• *Approach:* Incorporating research on wastes using life-cycle analyses such that overall environmental consequences are minimized or perhaps even enhanced

Environmental Issues of a Sustainable Future

• *Critical needs:*

– Better understanding of the role of the electricity sector in global sustainability.

– Understanding the local and regional environmental effects associated with alternative approaches to electrification (e.g., distributed resources vs. central station)

– Identifying and characterizing potential environmental impacts of advanced fossil generation (e.g., IGCC with carbon capture and sequestration, hydrogen production from fossil fuels, advanced coal cycles)

– Identifying and characterizing the environmental implications of the "hydrogen economy" (e.g., transportation and storage risks, waste products produced, issues associated with hydrogen production)

– Developing better tools to help planners and communities integrate electricity into sustainable urban settings

– Developing new approaches to allow market-based environmental management mechanisms to be used as a complement to non-market mechanisms

– Developing refined risk assessment methods to critically assess the costs and benefits of reducing or eliminating known or perceived environmental threats

• *Approach:* Integrating work on broad power system economic, environmental, and societal impacts, with key generation R&D initiatives

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APPENDIX

B Roadmap Origin, Influence, and Process

The original Roadmap—the 1999 Summary and Synthesis Report—was the culmination of a collaborative effort involving over 200 organizations. Working together, these groups established a compelling vision centered around five Destinations which are critical guideposts on the path towards the greater availability of environmentally sustainable power over the next 50 years.

In 2002, the Roadmap participants reconvened to extend the 1999 report to account for recent events (such as terrorist threats, growing infrastructure problems, and environmental concerns) and outline the 14 Limiting Challenges—the major R&D requirements essential to achieving the five Destinations.

The Electricity Technology Roadmap is a living document, owned by all industry stakeholders in the electricity enterprise, that is continually evolving as the world changes and research advances. The first edition of the Roadmap—the 1999 Summary and Synthesis Report—was intended to evolve over time alongside major geopolitical, economic, environmental, and technological changes. It defined five broad Destinations representing critical goals for ensuring the universal availability of cost-effective, environmentally sustainable power by the year 2050.

In 2002, EPRI initiated this first update of the Roadmap to reflect the intervening growth in knowledge and to provide a more detailed R&D plan for achieving the Roadmap Destinations. By coordinating the close collaboration of numerous organizations, including energy companies, equipment manufacturers, government agencies and research laboratories, academia, foundations, engineering and consulting firms, trade associations, financial organizations, and environmental groups, EPRI produced this 2003 updated edition of the Electricity Technology Roadmap, which identifies and addresses the most pressing energy industry R&D needs for achieving the Roadmap Destinations.

1999 Summary and Synthesis Report

The Electricity Technology Roadmap Initiative began in 1997. Although spearheaded by EPRI, over 200 organizations contributed to the framing of a shared vision based on five initial Destinations, which are:

- Strengthening the Power Delivery Infrastructure
- Enabling the Digital Society
- Boosting Economic Productivity and Prosperity
- Resolving the Energy/Environment Conflict
- Managing the Global Sustainability Challenge

For each Destination, the original Roadmap summarized the current technology development status, the barriers to advancement and commercialization (the "knowledge gaps"), the research initiatives needed to close these gaps, and the associated milestones, decision points, and order-of-magnitude budgetary estimates.

Overall, the 1999 Roadmap called for a research agenda of nearly $8 billion/year for 10 years, roughly double the U.S. R&D investment in these areas at that time.

Use of the 1999 Roadmap

Although there was considerable interest around the world in the initial Roadmap vision and recommendations, the efforts to mobilize support were overtaken by other events and priorities. Partly as a result, U.S. energy R&D expenditures have continued their 25-year decline, although it is fair to say that the Roadmap has improved the focus and value of the existing public and private R&D investments by the U.S. electricity sector. In the last few years, the Roadmap has served as an effective communications tool among institutions involved in energy technology development, and has helped focus the limited resources on those issues judged to be the highest priority by the community.

In addition, there has been significant progress in applying specific Roadmap recommendations to issues such as the Western states power crisis, the threats of sabotage and terrorism, and, most recently, the Northeast states power disruption. The Roadmap describes a clear path for developing the key technologies needed to prevent and mitigate similar problems with the power delivery system in the future.

A number of high-priority technology development initiatives identified in the 1999 Roadmap have been partially funded. Examples include:

- Carbon sequestration test centers
- Large-scale mercury field testing
- Boiler and steam turbine materials for advanced fossil fuel generating stations
- Technical basis for new nuclear plant combined licensing process
- Commercialization of distributed energy resources systems
- Self-healing power delivery system

Other Roadmaps Gain Momentum

Over the past several years, the general concept of roadmapping to provide clarity and direction to technological development has been gaining momentum. For example, the U.S. DOE has produced a number of critically important roadmaps as part of their "Industries of the Future" program. They have completed roadmaps on hydrogen, deploying new nuclear plants by 2010, technologies for advanced "Generation IV" nuclear plants, and various other categories of electricity uses. They are also actively exploring advanced coal generation and carbon sequestration. Similarly, the Dutch government has worked with EPRI and their own energy industry to create a Dutch Electricity Technology Roadmap. They found the five Destinations of the 1999 U.S. Roadmap appropriate, but added a sixth specifically dealing with transportation. And ESKOM, the South African utility company, has also adapted the roadmapping process to guide their electrification priorities. Finally, Electricité de France has developed a roadmap reflecting their own set of Limiting Challenges, which they call "De Fis."

As electricity- and energy-related roadmaps gain support throughout the world, the need for global dialogue on energy priorities is becoming apparent. This need supports the importance of continuously updating this Roadmap, further expanding its global outlook, and working to integrate diverse roadmap activities internationally.

Major Changes Since 1999

A number of events and issues—institutional, technological, and political—have changed the energy landscape and the nation's priorities since 1999, suggesting the need for a formal refinement of the Roadmap in 2003. In particular, energy security issues following the 9/11 terrorist attack have altered the nation's priorities. This has led to a reassessment of how critical infrastructures can be protected and made more resilient in the event of possible terrorist attack, and placed new urgency on reducing U.S. and global dependence on foreign oil supplies.

At the same time, electricity restructuring has become more complicated, its implementation uncertain, and its resolution more urgent. This situation has been exacerbated by the recent disruptions in investor confidence, the Western states power crisis of 2000–2001, and the Northeast states blackout of August 2003. In the aftermath of electricity trading scandals, the general public and their regulators have become more cautious and, in some cases, reticent to proceed with market reforms and clarifications. Given the policy and regulatory uncertainty, the ability of electric utilities to invest in the future has been seriously constrained. This has only increased the vulnerability of the U.S. power system.

Environmental issues have also continued to grow in seriousness and consequence. Many Roadmap participants believe that mandatory CO_2 constraints are likely within the next two decades, and power companies are beginning to factor that expectation, directly or indirectly, into their planning. As an emission-free source of power, the future of nuclear looks brighter than it did in 1999, aided by improved performance of current plants, turning points in current plant relicensing, and progress towards establishing a permanent repository for spent fuel at Yucca Mountain. The presumption of carbon constraints has also moved integrated coal-gasification combined-cycle (IGCC) generation technology, carbon sequestration, and hydrogen storage/delivery from the margins of consideration in 1999 to the status of serious options for the future. The mounting concerns over climate change and imported oil have also brought electricity-based transportation into the foreground.

Technology development has also made impressive progress since the 1999 Roadmap report, although the incentives for deploying the new technologies have not kept pace. There has been an increase in both the capability and use of power electronics, such as Flexible AC Transmission Systems (FACTS), to better control the flow of bulk power. At the other extreme, distributed energy resources (DER) technologies offer a means to locate power generation closer to the point of use, and to improve power quality for industries and businesses rapidly shifting to microprocessor-based, digital control technology. The advantages remain constrained, however, by the power distribution infrastructure. Until this infrastructure is converted from electromechanical to digital control, DER cannot be broadly assimilated as a reliability and capacity asset. Among the DER options, interest in the future of fuel cells is up dramatically, with billions of dollars now being spent annually on fuel cell development by governments, the auto industry, and others.

More Detailed Roadmap Development Process

The 1999 Roadmap report set out a long-term vision and interim Destinations in broad terms. Now, the 2003 Roadmap begins to lay out the terrain, allowing more detailed planning to help "build the road" to a more sustainable energy future. A formal effort to refine the initial Roadmap began in early 2002 with participants' confirmation of the continuing validity of the original goals and aspirations as captured in the five Destinations. The Roadmap's vision and five Destinations have held up well under four years of scrutiny by thousands of individuals and organizations.

The next step was identifying and reaching consensus on the most fundamental challenges that would have to be met to reach the Destinations within the original mid-century time target. This resulted in 14 "Limiting Challenges," with a planning team formed for each. These teams held workshops and individual interviews as a means to incorporate diverse viewpoints, as well as to gain technical insights. All those who participated did so with the understanding that their contribution to the process would not necessarily constitute endorsement of the Roadmap findings.

The workshops were used to help focus and frame the principal issues at stake in each of the Limiting Challenges. This led to selection of a handful of the most "critical capability gaps"—that is, key missing elements of knowledge and/or hardware capability—around which an R&D program could be designed.

Each of the teams has written a report of their findings and conclusions. The Limiting Challenges reports can be found on the EPRI website. For the reader's convenience, they are summarized in Chapter 6 of this report.

Conclusion

The main purpose of the current Electricity Technology Roadmap is to show opportunities and needs for the comprehensive modernization of the electricity supply system and how to take advantage of these opportunities for innovation. Unfortunately, there is a disconnect between the opportunities now being opened by advances in technology and the lack of commitment by both private and public institutions to seize these opportunities. In the U.S., that disconnect arises primarily from:

- The policy and regulatory impasse resulting from the continuing debate over electricity industry restructuring
- Lack of incentives for private investment in new infrastructure technology
- The lack of focused leadership and commitment to address these issues in a timely fashion

Similar trends can be found in most of the developed nations. Public and private investment in energy R&D has been declining for nearly two decades. But we are living in a period of profound societal and technological change. The investment choices made in such periods of change have profound consequences on whether future opportunities are realized or foreclosed, and whether threats to our society, environment, and economy are eliminated or left to worsen.

APPENDIX C TECHNOLOGY TIMELINES

This appendix provides short descriptions of (1) some of the key technologies that may play a critical role in the 21st century power system, (2) end-use technologies that will rely on tomorrow's power infrastructure, and (3) when these technologies (including their developmental precursors) could, with appropriate investment, be widely available. We recognize that our assessments will omit some important events and misjudge the timing of others. As is often the case in such forecasting, our projections are likely to be overly optimistic in the short term, but too conservative in the longer term.

Technologies are grouped according to seven areas of focus:

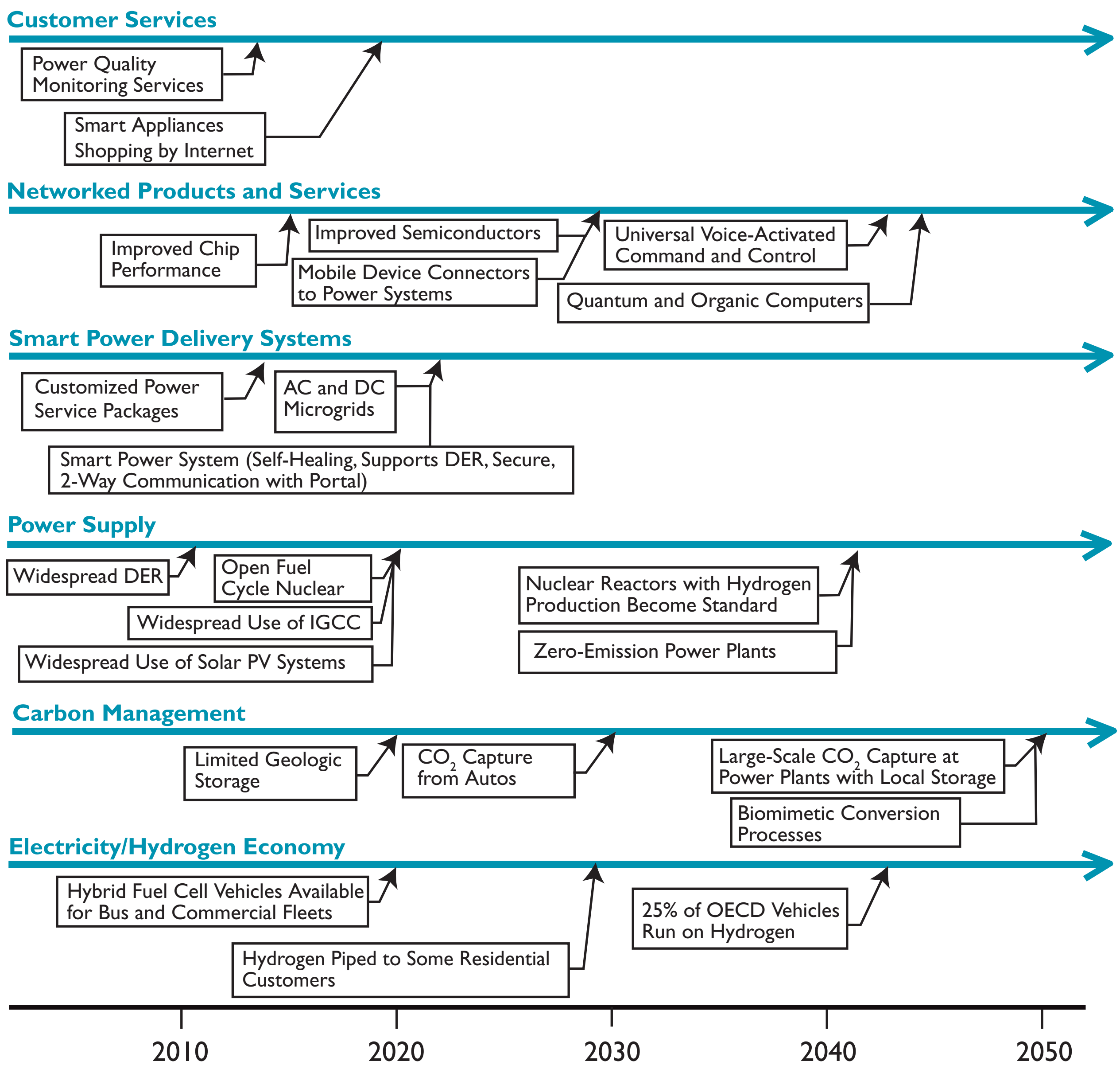
- Technologies That Revolutionize Customer Services
- Networked Products and Services
- Smart Power Delivery Systems
- Power Supply
- Carbon Management
- Electricity/Hydrogen Economy
- Wild Cards

Technologies That Revolutionize Customer Services

2010 Milestones

- Smart meters and two-way energy/information portals are widespread in some urban areas. Real-time pricing of electricity and connectivity with wholesale markets optimizes system performance and opens the potential to serve customers in new ways.
- Customer-based DER becomes an integral part of the electricity infrastructure.
- Real-time power quality monitoring services are widely available to businesses and for critical home functions, such as healthcare and computing.
- New energy efficiency software programs and services are delivered through the Internet.

Technology Timeline



Source: EPRI

FIGURE C-1. **This figure illustrates some key milestones on the way to achieving Roadmap technological goals.**

2020 Milestones

- Home appliances and business machines begin to shop and negotiate on behalf of their owners for power and services over the Internet. Purchasing programs for individual microchips are downloadable and customizable. Energy management at the individual device level becomes widespread.
- Smart appliances offer convenience features, such as monitoring the age, freshness, and replenishment of food in a refrigerator.
- There is growing use of appliances as grid resources. Water heaters or dishwashers, for example, are contracted to be taken off-line as needed to manage loads or prevent or mitigate the effects of a power disturbance.
- Control and monitoring of on-site and distributed generation provide system storage capability and open the door to mobile sources of generation, such as electric vehicles that go to work with their owners.

Networked Products and Services

As part of the 21st century transformation, the power delivery function will become intimately linked with other infrastructure elements, such as telecommunications and data networks, wireless devices, etc. This interconnectivity could provide the basis for the creation of a wide range of products and services, many based on communications. As this suite of products and services becomes available, it will become necessary to continually increase the reliability and quality of the power delivery system to meet the increasingly stringent specifications of the end-use equipment.

The massive data processing requirements implied by these networked technologies will place a premium on low-cost, high-performance chips that are also energy efficient. The "red brick wall" representing the ultimate limit of silicon microchip performance will be reached before 2010.

2010 Milestones

- Interim measures for improving chip performance include wafer-scale integration (capacitive coupling of chips reduces the need for wire connections) and "X"-wire configuration (connections on the diagonal of the chip, rather than in a rectangular grid). Next-generation chips provide higher data processing speed, lower power consumption, and lower heat rejection requirements.

2020 Milestones

- Diamond-based semiconductors become available, spurred by the development of methods for manufacturing large, gem-quality artificial diamonds. Diamond-based power electronics offer stable, high-temperature devices capable of switching high amperage at high standoff potential.

- The mobile phone and the laptop computer are connected to all network-dependent home and business services, including energy/information services delivered through a "smart grid" (described later). The phone is your operational center and your transaction hub for all financial information and transactions. Your laptop is your mobile office. Both the telephone and the laptop are linked to the power system through the energy /information portal.
- Networked autos are wireless media platforms, communicating real-time information on traffic conditions, detours, temporary speed limits, and parking.
- Internet Two is better organized, and contains more data and knowledge, than the current version. It also has interchangeable language capabilities. Global users have improved means for accessing, sorting, and evaluating data, thereby enabling global forums, education, polling, and shopping.

2030 Milestones

- Quantum and organic computing devices allow large increases in computing speed and dramatic enhancements in human interaction with the digital world.
- The "Open Sesame" technology platform offers voice control for virtually every interface with the digital world, starting with dictation and simple command and control, and expanding to include learning, home healthcare, and information retrieval. Applications and features explode as the market grows and specialized chips are developed. In practice, this may be similar to the growth of today's cell phone features. Open Sesame also supports the networked appliances of the future.

Smart Power Delivery Systems

Smart power systems will incorporate a large number of devices, the sensors to monitor their performance, and the data analysis systems to control operations and maintain reliability, power quality, and security. The elements of the smart power system will be implemented in a "plug-and-play" mode. New technologies that progressively enhance the performance of the system will be implemented as they become available.

2010 Milestones

- Power market simulations provide detailed evaluations of market-design options, as well as insights on alternatives for congestion management, system planning, and interregional coordination. These technologies reduce the need for "real-world experimentation," as in California.
- Different levels of service, quality, and reliability are offered to customers at different prices. Plain vanilla packages serve residential customers seeking price stability and certainty.

2020 Milestones

- Smart power systems are fully developed and widely deployed. They include self-healing capabilities, advanced distribution automation, distributed storage resources, and integrated communications architecture.
- Improvements in the security of the power system include ongoing probabilistic vulnerability assessments to help identify and prioritize critical susceptibilities. A secure wide-area communications network provides essential monitoring and control functions and improves the availability of information for system recovery. Emergency control and restoration systems ensure rapid recovery from events by coordinating adaptive islanding and grid self-healing.
- Fast simulation and modeling provide new levels of predictability of power flows, peaking conditions, congestion points, and aging equipment, as well as advanced methods of intrusion detection to foil hackers and terrorists.
- AC/DC microgrids emerge as islands of "perfect power"—industrial parks and urban cores, using power quality to attract and support high-tech and knowledge-based businesses.

Power Supply

Emphasis remains on developing a wider portfolio of clean power options and providing a transition pathway away from our overwhelming dependence on fossil fuels.

2010 Milestones

- Widespread deployment of DER, installed close to the point of use, reduces the need for additional power lines. Benefits include lower cost of power, higher reliability, and improved power quality.

2020 Milestones

- Integrated coal-gasification combined-cycle (IGCC) technology becomes the centerpiece of the modern coal fleet. IGCC plants produce an array of products, including electricity. (Achieving this milestone requires substantial development work before 2010, combined with pilot-scale and full-scale demonstrations in the 2010–2020 time frame.) In addition, IGCC plants are generally used in a continuous fuel-load operation mode, made possible by storage of energy in the form of synthesis gas. Many new IGCC plant staff have past experience at oil refineries and petrochemical plants, because their skills are more easily transferred to IGCC operations than those of standard power plant operators.
- Advanced open fuel cycle nuclear technology becomes the workhorse of an expanding non-emitting power generation infrastructure. The Roadmap target is to have 50,000 MW of new nuclear generating capacity online by 2020.

- Solar PV systems based on new materials, including nanotechnology approaches, are prevalent, and a serious contender for power and hydrogen generation around the world. The technologies include organic devices or direct splitting of water. Efficiency improvements are achieved through the development of a "one-photon" device, which splits water by absorption of a single photon.
- Environmental pressures to return rivers to their wild state reinforce a trend (already present) to take down dams in key wilderness areas and reduce the available hydropower resource. There is also pressure to replace the lost hydro resource with cost-effective renewable technologies.

2030 Milestones

- Nuclear reactors incorporating hydrogen production via electrolysis, thermochemical processes, etc. are standard design. These reactors provide the hydrogen and electricity to fuel the hydrogen electricity economy.

Carbon Management

Technology approaches include expanding emission-free generation and capture of CO_2 at the point of generation and sequestration in some environmentally safe medium.

2020 Milestones

- Limited storage of CO_2 is carried out in geological formations (such as salt domes and aquifers).
- Ocean storage remains problematic because of the difficulty in getting regulatory approval for dumping CO_2 on the sea floor, or for broad-scale iron fertilization of the ocean. (The uncertainties are considered too high, as are the downside consequences and liability questions if something goes wrong.)
- Terrestrial storage is pursued as an interim option, but reforestation has drawbacks—it is only capable of relatively short-term CO_2 take-up. After a while, the process saturates, or the trees die, and the oxidation process takes over.
- Other emerging technologies for sequestration are based on novel approaches, such as mimicking the biological processes of living systems, a process called "biomimesis." One example is the identification of the catalyst used by mollusks to speed the growth of their calcium carbonate shells, thus sequestering CO_2.

2030 Milestones

- Hydrogen-fueled autos offset CO_2 emissions because the hydrogen is produced by zero- or low-CO_2 emission technologies. Examples include electrolysis using nuclear, renewable, or low-carbon fossil fuel generation, and reforming hydrocarbons as a primary fuel—the latter with carbon capture and sequestration. The carbon capture and storage technologies are the same as for stationary generation, except for on-board reforming.

2050 Milestones

- Proven technology for large-scale capture of carbon at power plant sites is followed by long-term storage nearby (no long-distance travel needed for disposal). One technology relies upon the use of CO_2 as both working fluid and underground disposal medium (zero-emission power plants, or ZEPPS).
- Another example uses an industrialized application of biological processes to convert CO_2 into calcium carbonate (limestone), a scale-up of the biomimesis application described above.

Electricity/Hydrogen Economy

The combined use of hydrogen and electricity as energy carriers has the potential to improve the convenience of energy usage, provide new energy products and services, and deliver absolutely clean power at the point of use. However, the successful broad-scale use of hydrogen as an energy carrier is predicated on advances in technology for hydrogen production, storage, transport, and end use.

2020 Milestones

- Grid-connected hybrid fuel-cell vehicles become attractive options for commercial fleets and buses. The batteries are used for acceleration and passing, allowing the fuel cell to run at a constant load as much as possible. This eliminates the difficulties and inefficiencies of running the fuel cell and reformer at varying output levels.
- Hydrogen for vehicular uses is practical. Hydrogenated fuels are delivered in liquid, gas, or solid form (e.g., hydrides), affording on-board reforming.
- Another delivery option is recyclable "six packs" of hydrogen, where the user returns the empties to be cleaned, pressure tested, etc., before recharging. Fuel cells and "boxed fuels" are particularly suitable for rural areas and developing countries.

2030 Milestones

- Centrally produced hydrogen, delivered by pipe to the end-use customer, becomes available in some regions.
- Hydrogen is used for a suite of home electricity needs (via the home fuel cell) and for charging fuel cell vehicles.
- One fourth of OECD vehicle fleet consists of fuel cells and hybrids. They account for half of new OECD vehicle sales and one quarter of worldwide sales.

Wild Cards

Some of the most exciting technologies of the future are those that appear to be highly speculative from our current vantage point. Advances in these technologies will generally provide high societal and economic value. However, they usually pose large challenges in terms of technical feasibility, cost, political viability, or other factors. We include a sampling of these technology opportunities to illustrate how today's improbable advances could dramatically change the power system and provide value in unanticipated areas.

2020 Milestones

- High-conductivity (non-superconducting) materials, possibly made of carbon nanotubes or nanorods, provide substantial reductions in the cost of transmission capacity upgrades.

2030 Milestones

- The "Super Grid" approach uses materials that are superconducting at liquid hydrogen temperature. Hydrogen is both coolant and fuel. Large pipelines function as delivery mechanism, as well as a storage system.

2040 Milestones

- In hydrogen-based energy delivery by pipeline, electricity is generated via fuel cells "lining" the pipe. The waste heat from the fuel cells is used for hot-water heating and space heating. The hydrogen is combusted directly to supplement the fuel cell waste heat. The water produced in the fuel cells is collected and used for potable water and other applications.

APPENDIX D

Future Investment Requirements for Transmission and Distribution

This appendix documents the methodology, key assumptions, and results of a preliminary quantitative evaluation of the investment required to build the advanced "smart" power delivery system. Further work is needed to refine the approach used and perform sensitivity analyses on key variables that could affect the results.

This discussion is not intended to be a definitive analysis of all attributes of the power delivery system, but rather to stimulate discussion and help stakeholders align their cost projections for implementing a transformed electricity grid.

Overview

The current power delivery system in the U.S. cannot satisfy the increasing complexity of the marketplace or the increasing digital needs of the 21st century. Meeting the requirements of the future will require substantial upgrades in three broad categories:

1. Continuing to build for load growth and replacement of aging assets
2. Correcting deficiencies in the power delivery system and bringing it up to historical levels of reliability. Additional investment is needed to make up for reduced expenditures in recent years.
3. Transforming the existing infrastructure into the smart power system of the future that offers greater functionality for consumers and the ability to reliably support tomorrow's digital society. This is the focus of the Roadmap's technology development goals.

These three categories were used to estimate costs for both transmission and distribution upgrades. Importantly, the total cost of transforming the grid is not equal to the sum of the costs for load growth, correcting deficiencies, and system transformation. In fact, as described later in this appendix, the marginal cost of transformation is substantially less than the sum of the individual components. This is because many of the tasks in the first two categories can be performed in such a way that also addresses the needs for system transformation. Additional information regarding these cost reduction "synergies" is provided later in this appendix.

“Gold plating” the present power delivery system (e.g., simply pouring more money into the power delivery system in the form of redundant facilities with little regard for costs) is not a feasible way to provide the levels of security, quality, reliability, and availability (SQRA) that are required. Meeting the energy requirements of society will require applying a combination of current and advanced technologies throughout the electric power system, from generation busbar to end use.

The technologies needed to realize this future power delivery system include, but are not limited to, the following:

- Automation, the heart of a “smart power delivery system”
- Communication architecture, the foundation of the power delivery system of the future
- Distributed energy resources (DER), and storage development and integration
- Power electronics-based controllers
- Power market tools
- Technology innovation in electricity use
- A consumer portal that connects consumers and their equipment with energy service and communications entities

Transmission System Costs and Expenditures

To estimate the investment needed to upgrade the transmission system or “grid,” a top-down approach was used for the “load growth” and “correct deficiencies” segments, while a bottom-up approach was used for estimating the investment needed for the future power delivery system.

Transmission Load Growth. A preliminary estimate of the investment needed to meet future load growth was based on the annual transmission investment in shown in Figure D-1. Using data from the Edison Electric Institute (EEI) and the U.S. Department of Energy’s Energy Information Agency (EIA), Figure D-1 shows that annual transmission investment averaged about $7 billion from 1960 to 1985, and about $2.5 billion from 1985 to the present. The reduced investment rate during the latter period has proven to be about one half of that needed to adequately support demand growth. Based on previous experience, it is expected that keeping pace with continued load growth during the next 20 years will require about $100 billion, or $5 billion/year, in transmission investment.

Correcting Transmission Deficiencies. As a result of the investment decline over the past 20 years, a number of deficiencies have resulted, which must be addressed through the following corrective investments:

- Building more transmission lines and substations to improve power flow
- Planning and operating the transmission system to meet required equipment outage contingency conditions
- Improving and standardizing the communication and data protocol infrastructure
- Upgrading supervisory control and data acquisition (SCADA) equipment, upgrading energy management control center equipment, and training control center personnel
- Updating protection schemes and relays so that outages will not cascade into neighboring grid systems
- Performing proper transmission line and right-of-way maintenance, such as tree trimming

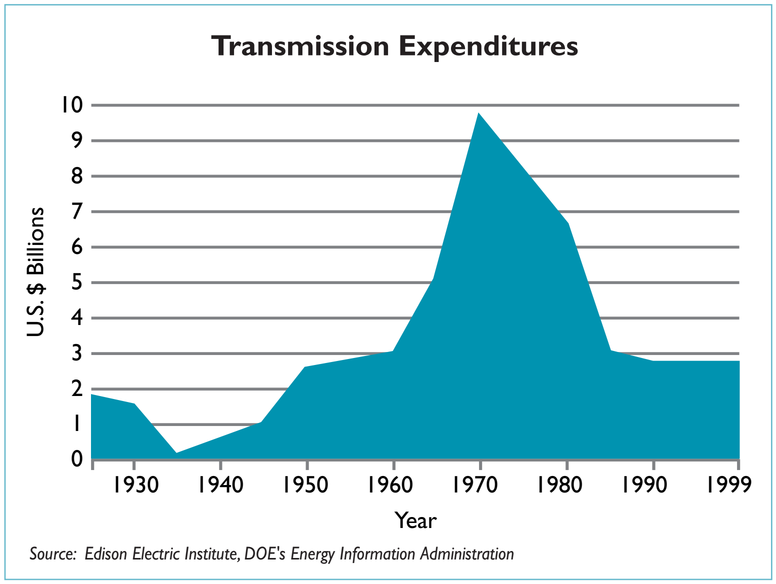


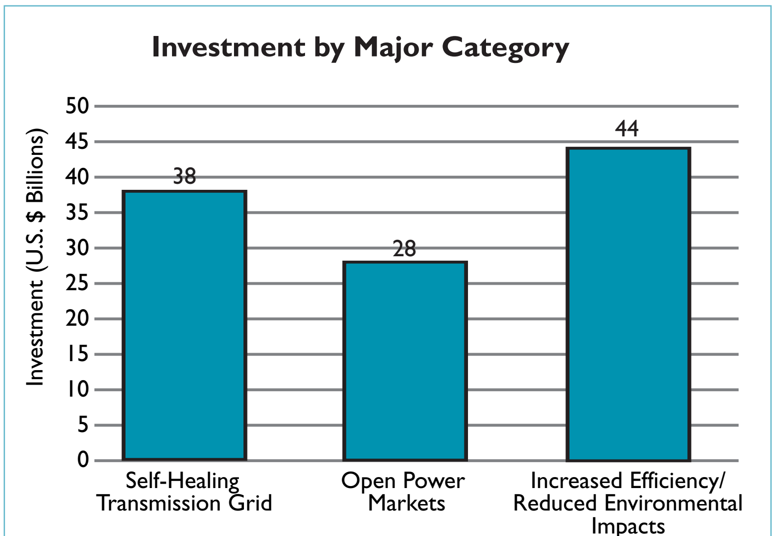
FIGURE D-1. This figure shows annual investments in the electric power delivery system in 2003 dollars.

Figure D-1 was also used to estimate the investment needed to correct deficiencies. The 1960–1985 average annual transmission investment of $7 billion resulted in temporary overcapacity and large margins. Subsequent declines in expenditures rapidly used up the overcapacity and reserve margins as demand grew. During the 1990s, the industry continued to invest less in transmission as a percentage of revenues than at any time since the Great Depression. The decrease in transmission investment was principally due to financial risk and uncertainties stimulated by the restructuring and re-regulation of the U.S. electricity supply system. The accumulation of deficiencies during this period was instrumental in creating significant transmission bottlenecks and other reliability-related issues throughout North America.

Now we need to reverse the trend and correct the deficiencies. Catching up will require compensating for the transmission investment gap created over the past 20 years, as well as accounting for future load growth. The additional spending should help mitigate the current boom-bust dynamic of transmission investment. In addition, more uniform spending in the future will allow the industry to incorporate the latest technology advances as they occur. Correcting deficiencies in the transmission system will require an incremental investment of about $50 billion.

Note that the correcting deficiencies portion of the upgrade process can, in general, be accelerated to a 10-year horizon. The deficiencies represent initiatives that, by definition, have been postponed. In fact, it may not be possible or desirable to extend the period for deficiency correction to the 20-year horizon used in other parts of this analysis. Since correcting deficiencies has so many synergies with load growth and system transformation, speeding the process will create significant cost savings.

Transforming the Transmission System. Unlike the top-down approach used to assess the investment requirements of meeting load growth and correcting deficiencies, a bottom-up approach was used for estimating the investment needed to transform the transmission system to meet the needs of the 21st century. The estimation process began by compiling a list of 14 critical technologies that will be needed for system transformation (see Table D-1). These technologies focus on communications and automation, intelligent monitoring and control systems, transmission efficiency improvements, and emergency response improvements. Development and deployment of these technologies could improve transmission system reliability by as much as 30–40%, while improving network efficiency, reducing grid blackout vulnerability, and improving security.



Source: EPRI

FIGURE D-2. This chart breaks down total investment requirements (approx. $110 billion over 20 years) for the transmission system of the future according to major R&D categories.

For each of these technologies, assumptions were made regarding the cost per unit to develop and deploy the technology, and the total number of units needed to realize the transformed transmission system. The product of these two numbers yields the total estimated investment needed over the 20-year period for each technology. Using this approach, the total projected cost of developing and deploying needed transmission technologies to realize the envisioned power delivery system in the United States is approximately $110 billion (about $5.5 billion/year).

Figure D-2 shows how the $110 billion investment is apportioned among: (1) the self-healing transmission grid, (2) open power markets, and (3) increased efficiency and reduced environmental impacts.

Synergies—Transmission Investment

Detailed analysis of the technology development requirements indicated that some of the technologies for load growth and correcting deficiencies also can advance the transformation of the power delivery system. For example, technical improvements that serve to increase transmission throughput will both help meet load growth and reduce congestion,

Table D-1. Estimation of Investment Needed to Develop and Deploy Advanced Technologies for Transforming the Transmission System			
High Voltage Transmission/Operational Technologies Required	**Development and Installation Avg. Cost/ Unit (U.S.$ Million)**	**Number of Units**	**Cost (U.S.$ Billion)**
Automation of transmission/substation systems	1	10,000	$10
Sensors/monitors and communication systems	0.01	400,000	$4
Energy storage shock absorbers	20	300	$6
Power electronics controllers, current limiters, and circuit breakers	50	200	$10
High-current/superconducting wires and cables	150	200	$30
Self-diagnostic transformers and other substation equipment	0.1	50,000	$5
Emergency operation controllers, relays, and tools	0.1	20,000	$2
Emergency restoration equipment/tools	1	10,000	$10
Faster than real-time simulation tools	1	1,000	$1
Probabilistic vulnerability assessment	1	1,000	$1
Higher-voltage lines/substations	100	100	$10
Reliability-centered/predictive maintenance	1	20,000	$20
Dynamic thermal circuit rating	0.5	1,000	$1
Power delivery system planning tools	1	500	$1
TOTAL (U.S.$ Billion)			**$110**

Source: EPRI

thus mitigating some of the deficiencies in the current power system. Similarly, substation automation will increase capacity and simultaneously provide a major advance in developing the smart power delivery system. Taking advantage of these "synergies" can substantially reduce the overall cost of developing the future power system.

Past experience with cost estimation suggests that about 25% of the load growth investment, or $25 billion, would also be applicable for transforming the grid into the smart power system of the future. Likewise, about 75% of the deficiency correction activities, with a value of $38 billion, will also contribute to the future system. Finally, about 10% ($10 billion) of load growth initiatives will also serve to correct deficiencies.

In summary, without consideration of synergies, the estimated transmission investment over the next 20 years would total $260 billion ($100 billion for load growth + $50 billion for deficiencies + $110 billion for power delivery system advancements). But this number is reduced by $73 billion to an estimated $187 billion ($9.4 billion/year) after accounting for the synergies. This represents a tripling of the currently projected "business-as-usual" industry investment of about $60 billion ($3 billion/year) over the next 20 years.

Distribution System Costs and Expenditures

Power disturbances experienced by consumers are mostly influenced by the distribution system. Reliability is typically measured as the number of outages and the average total duration of interruptions (i.e., "minutes lost") experienced by a consumer in a year. Over 90% of the minutes lost for consumers are attributable to distribution events. Investments in the distribution system are required to achieve higher levels of reliability, and these investments will have the following additional important advantages:

- Improved asset management
- Reduced losses on the distribution system (via better voltage/VAR management)
- Complete integration of DER to provide more flexibility in overall system energy management
- Integration with consumer systems to provide a new array of services and allow the use of consumer systems to improve overall energy management

Upgrades to the distribution system fall into the same three categories as for transmission system upgrades and investments:

- Load growth and replacement of aging equipment
- Correcting deficiencies
- Smart distribution system

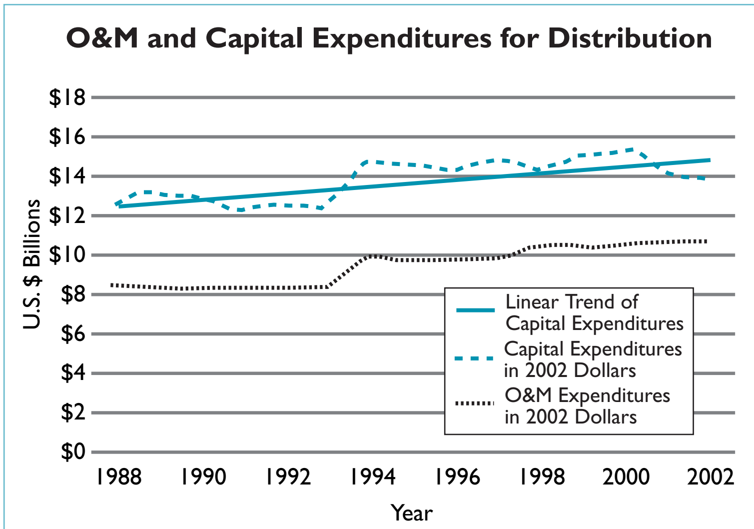
However, there are some significant differences between transmission and distribution. First, the investment requirement for distribution load growth is more than 6 times larger than for transmission. This is the result of the larger scale of the distribution system. Distribution systems have more wires, substantially greater total miles of wiring, and a larger inventory of equipment than transmission systems.

Second, the distribution equipment on a typical feeder circuit is sized to meet the peak electrical load in a particular location, while transmission equipment feeds power to a much larger region. Since peak loads vary from area to area at any point in time—depending on weather, customer mix, and other factors—transmission equipment can generally have a lower capacity than the sum of all the distribution equipment in an area.

Third, because of the need to change rapidly to meet evolving demand, deficiencies in the distribution system tend not to accumulate to the same degree as deficiencies in the transmission system. Consequently, the "correction of deficiencies" element of the distribution system upgrade is of minor importance compared with the transmission system.

Distribution Load Growth. Distribution load growth is highly dependent on economic conditions. A growing economy supports more homes, more factories, and more commercial buildings. These, in turn, increase the requirements for more distribution substations, more feeder circuits, more transformers, and more voltage regulators. And because this equipment must be sized to meet anticipated peak demand, upgrades of distribution systems will be correlated in time with, and may precede, economic growth.

To estimate future investment needed to meet load growth and normal equipment replacement requirements, the analysis used historical EIA data on annual capital expenditures for distribution since 1988, adjusted to 2002 dollars (see Figure D-3). The trend line for these data shows that annual capital expenditures are increasing at about 1% per year, and the expenditure level stands today at about $15 billion annually for capital expenditures in 2002 (actual expenditures in 2002 were below the line). Assuming that this capital investment in distribution continues to increase at 1% per year, cumulative expenditures over the next 20 years will be about $330 billion. This is the aggregate needed to keep up with normal system investment requirements for load growth and equipment replacement.



Source: DOE's Energy Information Administration Database, 2002

FIGURE D-3. This figure illustrates historical distribution system investment adjusted to 2002 dollars.

Correcting Distribution Deficiencies. As mentioned above and shown in Figure D-3, distribution companies have done a reasonably good job of keeping pace with needed upgrades, and the cumulative deficiencies are minor relative to transmission. Some of the deficiencies include circuit overloading, limited ability to integrate DER on the grid, and difficulty in implementing demand response systems. Catching up with deficiencies will require an estimated additional cumulative investment of approximately $5 billion. Due to the short-term nature of distribution equipment needs, it should be possible to correct these deficiencies in, at most, five years.

Smart Distribution System. The smart distribution system investment includes the automation of the entire distribution system, the development of topologies that allow automated islanding and reconfiguration, the full integration of DER, and the seamless interconnection with customers through the energy/information portal. The specific areas for investment are described below. They add to $260 billion over 20 years and include:

- *Substation automation.* This involves providing high-bandwidth communications to all substations, implementing intelligent electronic devices that provide adaptable control and protection systems, integrating complete monitoring systems with asset management systems, and adding intelligence to improve reliability and system operations. This will also improve power quality and prevent overloading of circuits. The total cost estimate for substation automation is $25 billion.
- *Automating distribution feeder circuits and DER integration.* This means automating the switches on the system to allow automatic reconfiguration, automating the integration and operation of DER, and optimizing system performance through voltage and VAR control to reduce losses and improve power quality. The estimated cost of automating distribution feeders and integrating DER is approximately $173 billion.
- *Complete seamless interconnection with customer systems.* This will allow the implementation of flexible pricing based on actual energy costs, as well as meeting the different reliability and quality requirements of customers. The transformed system functionality will also enable a wide variety of enhanced higher-value energy/information services. The cost of connecting with customer systems is estimated as $62 billion.

Synergies—Distribution System Investment

As in the case of transmission investments, synergies among the categories of distribution investments can reduce the overall cost of future distribution investment. Understanding these synergies can reveal opportunities to focus capital investment in high-return areas. For example, initial investments to automate distribution substations will emphasize high-bandwidth communications to all substations and intelligent electronic devices (IEDs) that provide adaptable control and protection systems. These actions will reduce deficiencies and mitigate the need for new distribution capacity, in addition to being a critically important element in the future distribution system. Without these synergies the overall cost is approximately $595 billion ($330 billion for load growth + $5 billion for correcting deficiencies + $260 billion for the future distribution system). The synergies lead to a cost reduction of $132 billion, leaving $463 billion ($23 billion/year) as the total distribution cost requirement over 20 years. This represents a 40% increase over the 20-year business-as-usual projected expenditures of $330 billion ($16.5 billion/year).

Table D-2. Comparison of Transmission and Distribution Investment Needs by Segment

	Transmission Investment (20-Year Total, U.S.$ Billions)	Distribution Investment (20-Year Total, U.S.$ Billions)
Meeting Load Growth	$100	$330
Correcting Deficiencies	$50	$5
Transformed Power Delivery System	$110	$260
Total Cost (Without Synergies)	$260	$595
Savings Due to Synergy	($73)	($132)
Total Funding Requirement (With Synergies)	$187	$463
Total Expenditures at "Business-As-Usual" Rates	$60	$330
Additional Funding Needed Beyond "Business-As-Usual"	$127	$133
Additional Funding Needed per Year Over 20 Years (U.S.$ Billion/Year)	$6.4	$6.6

Source: EPRI

Conclusion

The costs of system transformation are summarized in Table D-2. The table shows the cost of load growth, correcting deficiencies, and the transformation of the power system, and it displays the sum of these elements without taking credit for the synergies deriving from the overlap of portions of program content. The savings generated by these synergies reduce the overall cost by $73 billion for transmission and $132 billion for distribution. The table also compares the funding requirements (accounting for synergies) to current expenditures. The incremental funding needs are $127 billion for transmission and $133 billion for distribution, respectively.

These estimates indicate that developing the power delivery system for the 21st century will be costly, but not prohibitively expensive in light of historic investment patterns. The incremental cost of both transmission and distribution transformation is about $13 billion/year, or 65% over and above current business-as-usual investment of about $20 billion annually.

It's important to note the importance of the timing of critical activities in transforming the power delivery system. A phased approach to system implementation will allow the utility to capture many of the cost synergies described in this paper. Equipment purchases, for example, should emphasize switchgear, regulators, transformers, controls, and monitoring equipment that can be easily integrated with automated transmission and distribution systems. Long-term plans for equipment upgrades should also address system integration considerations.

Finally, it's evident that the scope of transforming the U.S. power system is a major undertaking that can only be accomplished through consortia involving the key public and private stakeholders in the electricity enterprise. Acting through these consortia to build the initial versions of the transformed power system can create the momentum needed to sustain the development and funding process over the 20-year time frame envisioned in this report.

APPENDIX E

Roadmap Linkage with U.S. Government Energy Policy Documents

Key to developing a plan and process (including roles and responsibilities) for the public and private sectors to work in partnership on critical energy R&D needs is understanding how closely aligned these sectors are today on the goals that must be achieved. Table E-1 compares the goals of the National Energy Policy, the DOE Strategic Plan, and this Roadmap. The commonality between these three visions of the future, particularly for the next 20–30 years, is striking.

It is important to appreciate why electric utility industry leaders share interests with national energy policymakers when it comes to planning and budgeting for energy R&D. Both support preserving the strategic and economic advantages of a diverse energy supply portfolio. Both are acutely aware of the need for reducing the cost and increasing the strategic value of R&D. Both are challenged by taxpayers and ratepayers to deliver safe, reliable, and cost-effective power to all consumers, using fuels, supply technologies, and transport methods that sustain natural resources and environmental quality. And both are vitally interested in leveraging the strengths of U.S. energy technology and economic vitality to compete in world energy markets, thereby improving balance of trade and expanding high-tech domestic job opportunities. These shared interests and objectives should encourage joint planning, prioritizing, and resource management.

Table E-1. Side-by-Side Comparison of the Electricity Technology Roadmap with the National Energy Policy (NEP) and the DOE Strategic Plan

Roadmap Destinations	NEP National Goals	NEP Challenges	Roadmap Limiting Challenges	DOE Strategic Plan: Strategies and Intermediate Objectives
Strengthening the Power Delivery Infrastructure	Modernize Our Energy Infrastructure Increase Energy Security	Repair and Expand Our Energy Infrastructure	• Increase transmission capacity and automate the transmission and distribution grids • Develop a secure energy infrastructure	• Predict and improve T&D reliability, security, and market efficiency • Reduce vulnerability and increase reliability of electricity supplies, focusing on superconductivity and distributed generation • Improve the performance of transmission lines by removing bottlenecks
Enabling the Digital Society			• Develop market designs incorporating the energy/information portal for electricity and services • Develop and implement advanced storage technology • Create the infrastructure for a digital society	• Develop technologies for distributed generation, including relatively small-scale and modular energy generation devices
Boosting Economic Productivity and Prosperity	Modernize Conservation	Use Energy More Wisely	• Expand opportunities for digital energy efficiency • Develop electricity-based technologies that will enable economic growth • Pursue options for electric-drive vehicles	• Develop and bring to market energy efficiency technologies

Roadmap Destinations	NEP National Goals	NEP Challenges	Roadmap Limiting Challenges	DOE Strategic Plan: Strategies and Intermediate Objectives
Resolving the Energy/ Environment Conflict	Accelerate Protection and Improvement of the Environment Increase Energy Supplies	Increase Energy Supplies While Protecting the Environment	• Develop and maintain a diverse set of electricity generation opportunities • Develop and deploy commercial integrated coal-gasification combined-cycle (IGCC) plants • Promote fundamental break-throughs in the cost of renewable energy; address renewables' intermittency issues • Expand nuclear generation and reduce the obstacles to its greater use • Improve the cost and efficiency of fuel cells and other distributed generation options • Apply hydrogen as an energy carrier • Develop tools for carbon capture and sequestration	• Lead international effort to pursue advanced nuclear technology • Assure availability of nuclear fuel to meet supply interruptions • Accelerate hydrogen programs by developing technologies to produce hydrogen using renewables, nuclear, and fossil fuels • Develop fuel-cell power technologies • Develop new technologies to increase domestic oil and natural gas supplies • Research renewables and work with private sector to develop them • Advance plasma and fusion science to support the long-term commercial application of fusion power • Reduce emissions of coal-based power facilities and pursue sequestration
Managing the Global Sustainability Challenge			• Develop technologies for global electrification, with greater emphasis on low-emission and emission-free sources • Identify emerging opportunities to improve water availability and quality • Resolve the environmental challenges of powering tomorrow's global economy • Employ asset management tools to make critical decisions on energy policy/technology issues	

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EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com