

THE INTEGRATED ENERGY NETWORK

CONNECTING CUSTOMERS TO RELIABLE, SAFE, AFFORDABLE, AND CLEANER ENERGY



FOREWORD

Over the past few years, EPRI has examined the forces changing the world's energy systems. We have gained insights through discussion with our Board of Directors, Research Advisory Committee, public-mission Advisory Council, and with leaders from energy businesses, regulatory commissions, academic institutions, scientific and environmental organizations, finance, and government.¹

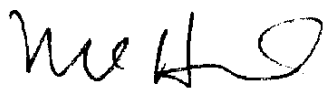
These conversations have revealed that systems for managing energy and natural resources are increasingly interconnected. Yet these systems remain largely separate and fragmented with respect to strategy, management, and operations. Technological change is amplifying the cost of failing to integrate these systems while also creating new opportunities and rising customer expectations with respect to reliable, affordable, and cleaner energy. Many customers also seek greater control of their energy options.

To realize the opportunities arising from such change requires fundamentally different thinking. Here we outline steps—the Integrated Energy Network (IEN) pathway—to articulate how the actions of diverse interests could yield more integrated, efficient, and productive management of energy and natural resources.

As a result of this assessment, EPRI will make changes we believe are needed to fulfill our mission, “Advancing safe, reliable, affordable, and environmentally responsible electricity for society through global collaboration, thought leadership, and science and technology innovation.” We will:

- **Refocus our research.** We will look more broadly at the changing interconnections between electricity, gas, water, transport, other energy carriers, and natural resources such as water and clean air. We will investigate also new customer expectations and opportunities in the broader context of these interconnected industries.
- **Broaden our membership** to encourage diverse entities to participate in our collaborative research.
- **Expand our communication and outreach** to increase engagement with participants across the energy sector and to more constructively engage with diverse stakeholders.
- **Expand internationally** to bring to our R&D collaborative the broadest possible perspectives, knowledge, ideas, and approaches.

We offer this document to spark new thinking and discussion about how integration can affect the production and use of energy. As we publish a series of supporting technical documents and launch new R&D efforts we seek your input. Our website at <http://ien.epri.com> offers more information and various ways for you to help us develop this pathway. We look forward to your engagement.



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¹ EPRI's Board of Directors and Research Advisory Committee are comprised primarily of leaders from EPRI's global membership. EPRI's Advisory Council consists of leaders from regulatory, academic, environmental, financial, and scientific organizations. While all provided thought and guidance, the views represented in this document, unless otherwise stated, are EPRI's and do not necessarily represent the views of the members (individually or collectively) of those bodies, or of EPRI's funders and members.

THE FUTURE OF ENERGY: A PERSPECTIVE AND PATHWAY

Over the past 12 years the world's population grew by 1 billion, passing 7.3 billion in mid-2015. Credible projections envision further growth to about 11 billion by 2100.² Most people live in cities today, for the first time in history, and almost all of the anticipated population growth is projected to be urban. The global economy is expected to expand three to four times faster than population, substantially increasing the demand for energy services.

This growth affects an array of local and global environmental challenges. Competition for scarce water resources is already evident in much of the world. Concern about air and water quality is rising—especially in emerging economies—even as tremendous progress is made in managing pollution. The World Health Organization (WHO) recently concluded that 92% of the world's population lives in places where air pollutant levels exceed WHO limits.³ Globally, nations are joining in efforts to limit emissions of greenhouse gases, most of which come from the energy sector. As environmental pressures grow, and as societies become wealthier and more aware of the issues at stake, they expect that their energy systems will deliver more services at a reasonable cost and with a much lighter environmental footprint.

Along with these rising demands and expectations, the technological capabilities for energy supply and environmental protection are changing quickly. In the past, the systems that provided customers with energy services such as lighting, communication, mobility, and clean water developed largely independently. Looking to the future, new technologies and business models are making feasible a much deeper integration of these services. These changes offer the opportunity for societies and firms to rethink how they organize and provide energy and natural resource services.

Much of the technological transformation is rooted in rapid, pervasive digitalization. By 2016, more than 50% of U.S. residential electricity customers were equipped with smart meters.⁴ The European Union expects more than 70% of customers to have smart meters by 2020,⁵ and deployment is proceeding rapidly in Latin America and Asia. Power plants and transmission and distribution assets are being retrofitted with sensors to operate more efficiently and in ways that allow much more precise environmental control. Markets—still nascent in much of the world—are creating price signals that reward better and more integrated operations. Ongoing deployment of smart devices prompts some to project that within a decade or so essentially every grid-connected device will have its own internet address—from light bulbs to the many components of electric vehicles and nuclear power plants. Natural gas and water systems also are digitizing, although at a pace generally slower than the electric sector. Intelligent sensors, automation, and real-time data offer more information, choices, and control to customers and provide new ways to optimize energy systems. They also raise customer expectations—prominent among them the demand for much more reliable supplies of electric power needed to power digital systems.

² World Population Prospects – 2015 Revision. United Nations.

³ World Health Organization. News release on September 27, 2016.

⁴ Institute for Electric Innovation, *Electric Company Smart Meter Deployments: Foundation for a Smart Grid*, October 2016, available at: <http://www.edisonfoundation.net/iei/publications/Documents/Final%20Electric%20Company%20Smart%20Meter%20Deployments-%20Foundation%20for%20A%20Smart%20Energy%20Grid.pdf>

⁵ European Commission. 2016. "Smart Metering Deployment in the European Union." <http://ses.jrc.ec.europa.eu/smart-metering-deployment-european-union>.

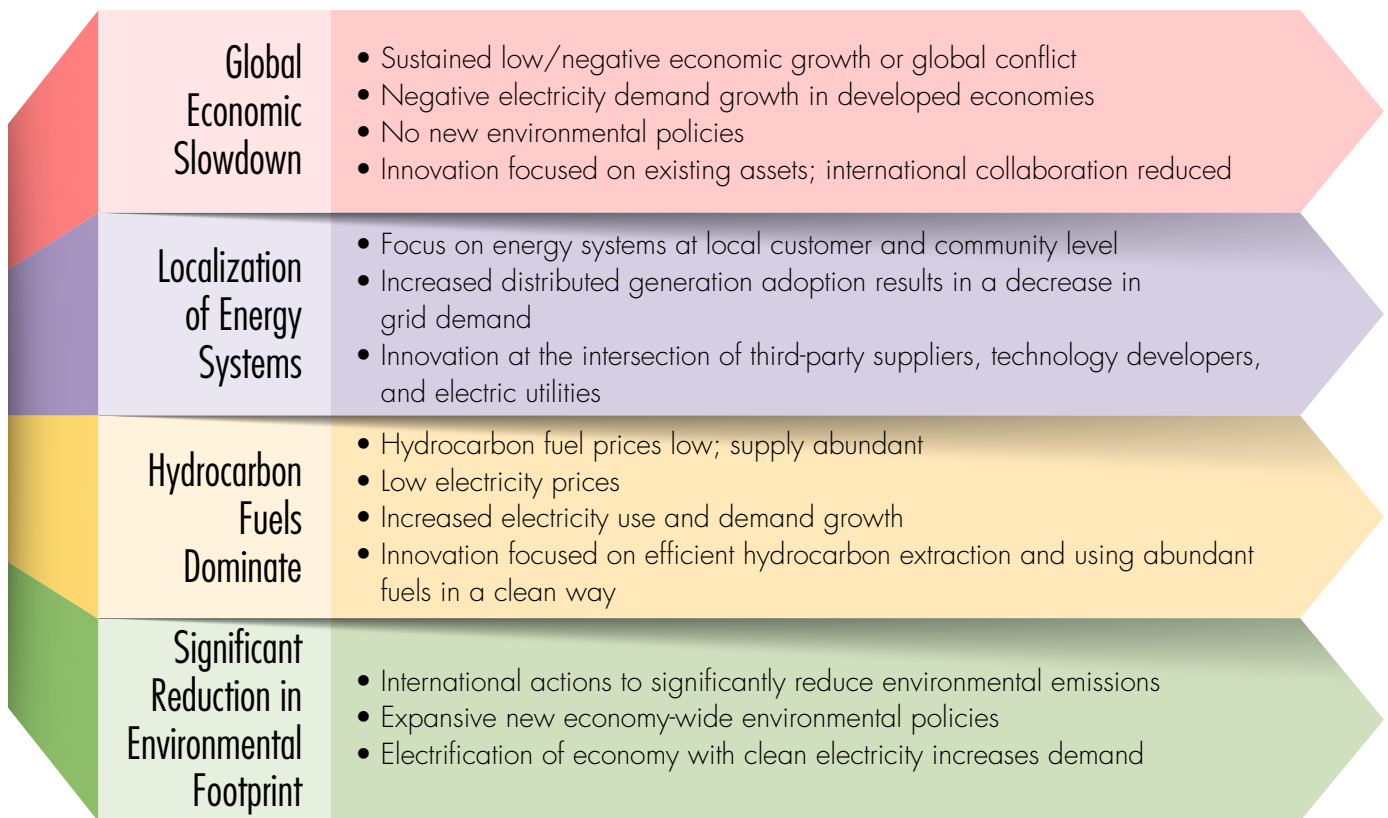


Figure 1. Bounding Scenarios.

With these trends in mind, in 2015 and 2016 EPRI convened a range of stakeholders to explore their expectations for the energy industry and how the future may unfold. Our discussions were informed by many diverse sources of information including an array of studies recently published by government, academic, and private organizations.^{6,7,8}

To structure discussion, EPRI developed four bounding scenarios—each driven by alternative views of such forces as demand for energy services, the price of hydrocarbons, energy and environmental policies, human behavior, and innovation (Figure 1).⁹

From these, EPRI developed *Global Points of View* to summarize the insights that hold in most, if not all scenarios, excerpted below. These scenarios and points of view help to map plausible futures for the world's energy systems. Energy companies and stakeholders can use these to explore causes and consequences of transformations in how society produces, trades, and uses energy.

⁶ Several studies focus on the specific aspects of the energy future. For example, Risky Business, *From Risk to Return: Investing in a Clean Energy Economy*, November 2016. Obama Administration, *United States Mid-Century Strategy for Deep Decarbonization*, November 2016. MIT, *Utility of the Future*, December 2016. US Department of Energy, *Transforming the Nation's Electricity System: The Second Installment of the Quadrennial Energy Review*. January 2017.

⁷ Some studies explore the links between energy and natural resources. For example, BP, *Water in the energy industry: An introduction*. <http://www.bp.com/content/dam/bp/pdf/sustainability/group-reports/BP-ESC-water-handbook.pdf>. 2013.

⁸ There are fledgling efforts to understand energy system integration from a technical perspective. For example, EPRI participates in the International Institute for Energy Systems Integration, <http://iiesi.org/>, which aims to explore many of the technical issues associated with energy systems integration.

⁹ For a fuller description on the scenarios EPRI developed and a full listing and details associated with the Global Points of View, see *A Perspective on the Future of Energy: Scenarios, Trends, and Global Points of View*. EPRI 3002009918. February 2017.

*Excerpts from EPRI "Global Points of View"
to the 2030s and Beyond*

- The global economy expands fueled by significant growth in energy use, coupled with significant reduction in energy's environmental footprint, in response primarily to regional environmental issues, but increasingly in response to global issues such as climate change.
- Efficiency emerges as a social, economic, technological, and operational trend across the energy sector. In emerging economies increased demand for energy services leads to increased energy use. In developed economies, efficiency gains outweigh energy service growth, leading to flat or declining energy use.
- Electricity demand grows more rapidly than overall primary energy demand, continuing a century-long trend. Technological advances and strengthened environmental policies could greatly accelerate electrification.
- The transportation sector reaches much higher efficiency, incorporates intelligence and communication technologies, and moves to low-carbon fuels, including electricity.
- Greater value and expectations are placed on power quality and reliability.
- Central-station generation, including nuclear, gas, coal, and renewable, and the electric grid continue to serve an anchor role in providing reliable, affordable electricity. These technologies evolve to enable productive use of a more diverse energy portfolio in developed economies. For emerging economies in which new transmission is constrained or costly, they support deployment of local grids and distributed resources.
- Renewable energy deploys rapidly and globally through electricity and via direct application of biofuels and other energy carriers in non-electric portions of the energy system. Distributed power applications require modernization of distribution and transmission systems enabled by integrated communications and control.
- Integration of system planning and customer information enables greater efficiency and control, and creates new opportunities and challenges for security and resiliency.
- Connections between electricity, other energy sources, and water take on greater importance. Emerging technologies such as electric vehicles and an array of hydrogen applications create new connections.
- Innovation accelerates, with new technologies and business models increasingly coming from sources outside the traditional energy industry.

THE INTEGRATED ENERGY NETWORK

Emerging from EPRI's analysis is the essential insight that society and the industry should welcome and accelerate the tighter integration of energy systems. Services traditionally provided by diverse and disconnected systems—such as heating, lighting, transport, and industrial automation—should be provided through a more integrated system of systems. Moreover, energy services need to be better integrated with the resources they utilize. EPRI calls the desired end-state of this process the Integrated Energy Network (IEN) and the near-term steps towards this destination, the IEN pathway. The IEN frames a future in which customers have flexibility to use, produce, and manage energy efficiently, in ways they prefer, with access ensured to all for reliable, safe, affordable, cleaner energy.

The Integrated Energy Network won't happen automatically

Making the IEN a reality requires new thinking on many fronts, breaking from current trends and practices. For example, it will require energy companies, policy makers, and the R&D enterprise to:

- Manage energy and natural resources as an integrated system. Separate regulation, planning, and operation of electricity, natural gas, and water systems have made these systems less reliable and efficient, and they make it harder to realize the productivity and environmental gains of deeper integration.
- Guide an efficient transition to much more digital, dynamic, and networked energy systems, which will require significant technology advances and infrastructure investments coupled with secure and private communication, control, and operational standards.
- Accelerate the development of cleaner energy technologies—supply, demand, delivery, and storage technologies—that can operate more flexibly, ensuring the reliability of energy services while emissions are reduced significantly.

- Unleash and promote opportunities for efficient electrification, the essential path to a more efficient, cost-effective, and cleaner energy system.
- Create new business models that build on the strengths of today's energy infrastructure while taking advantage of new technological possibilities.
- Increase energy system resiliency and security while protecting privacy.

The IEN pathway envisions not just physical interconnections among these energy systems and resources. It is rooted in pervasive, secure interconnections of data, information and market signals that can enable much more sophisticated monitoring and control of energy networks, and expanded customer choice. Indeed, increased choice and information interconnections are at the root of many current industrial transformations.¹⁰ Developments in those industries perhaps foreshadow new patterns in the propagation of ideas and market signals through energy industries. A prominent example is the importance of battery technology for transportation, grid operation and services, and water movement. Technology advances in one application can give rise to profound changes across the energy and natural resource systems.

The IEN pathway also illuminates the critical role of electrification as a means of integration and achieving greater value. Where fossil fuels are combusted directly today—such as within onboard engines in cars and trucks—electricity will increasingly become the carrier of useful energy. Electricity's role has been steadily growing since its commercial introduction in the 1880s. Accelerated electrification may well emerge as the keystone to enhancing efficiency, improving productivity, and providing cleaner energy.

The IEN extends EPRI's earlier thinking regarding electric sector challenges. In 2014, EPRI introduced its Integrated Grid concept, aimed at maximizing the value of central and distributed electric resources.¹¹ EPRI views the Integrated Grid as an essential enabler of the Integrated Energy

¹⁰ McKinsey Global Institute. "A Future that Works: Automation, Employment, and Productivity". January 2017.

¹¹ See <http://integratedgrid.com> for a series of reports and opportunities to get engaged in this vital, on-going effort.

Network. The IEN expands the Integrated Grid concept in many dimensions. For example, IEN includes a comprehensive, integrated consideration of the environmental consequences of all choices while the Integrated Grid addresses environmental issues only indirectly. The IEN also expands the range of options considered for addressing key challenges such as balancing load with variable renewable and distributed energy resources. While the Integrated Grid considers dynamic options in power production, delivery, and use to balance this variable generation, the IEN considers a much wider array of traditionally “arm’s length” options such as natural gas storage, thermal storage, creation of new flexible demands such as electric transport, or integration with potential future energy carrier systems such as hydrogen.

The IEN, taken to its fullest extent, suggests the need for a fundamental rethinking of an energy system that has evolved gradually for most of the past century. This transformation could rival the late nineteenth and early twentieth century when the basic elements of the modern electricity industry emerged. As new electric options were introduced, it took several decades for industry and households to adopt them, and in the process, many vital social and industrial functions were created and transformed. Homes gained lighting and refrigeration. Industry used these decades to redesign factories to make new products or make existing products in new ways, resulting in much greater economic efficiency. This paper proposes that the IEN can help prompt similarly fundamental change and create new, unforeseen opportunities as diverse energy industries and services become more interwoven.

Integrating production, delivery, use, and control of resources

In considering the complex, multi-dimensional global energy sector, the IEN examines its systems from three perspectives:

- ***Using Affordable, Cleaner Energy – through efficiency and electrification.*** From this perspective, consumer desires for reliable, affordable, cleaner energy combine with expanded choice and control. The pace of electrification accelerates as electricity use provides

a cleaner energy alternative, while remaining affordable and reliable. Improved energy efficiency results from both environmental stewardship and advances in consumer technologies.

- ***Producing Cleaner Energy – through more efficient and environmentally sustainable, and flexible generation.*** Energy service providers reduce costs and environmental footprint while operating more flexibly, leading to wider use of electricity as an energy carrier. Renewable energy plays a growing role, and hydrogen potentially emerges to meet some energy needs.
- ***Integrating Energy Resources – through new control technologies, communications, standards, and markets.*** Improved control of electric systems, coupled with communication and security protocols and online systems, support interoperability of connected systems. Integration of distributed generation and the grid improve system productivity and flexibility. This enables broader, coordinated management and control of energy and other resources that improves reliability and efficiency. Electricity emerges as the central, essential means to improved energy efficiency and environmental sustainability.

Each of these perspectives is introduced below. EPRI will release additional technical papers in 2017 to further develop these perspectives (see <http://ien.epri.com>).

USING AFFORDABLE, CLEANER ENERGY – THROUGH EFFICIENCY AND ELECTRIFICATION

A central driver of the Integrated Energy Network is the demand for affordable and cleaner energy. Expanding urban populations with rising income levels expect this. An array of technological advances make obtaining cleaner energy more affordable today than ever before, while expanding customers' choices and control.

Efficiency gains are essential to cleaner energy. From a customer's perspective, some efficiency gains require investments (e.g., insulation, new lighting) while others come essentially at no additional cost, such as power-saving innovations in portable electronics spreading to other products.¹²

Electrification enables a more productive, efficient, and cleaner energy system

Electrification—customers' shift from direct combustion of fossil fuels to electricity—has emerged as a valuable strategy for not only boosting efficiency, but also for reducing emissions at minimum cost. While acknowledging those circumstances in which it remains more efficient or less expensive to burn fossil fuels directly, there is a growing array of energy uses for which electricity is the best option—especially where pollution must be cut nearly to zero, such as in densely populated cities. For example, with today's technologies, sending electrons to vehicles can be more than twice as energy efficient while reducing local emissions to zero. Electrifying vehicles in this case can also reduce the cost of fuel by 70% while lowering emissions of CO₂ by 75%.¹³ Another important example is space heat. By *moving* heat rather than *creating* heat via gas combustion in a furnace, an electric heat pump requires significantly less primary energy. Heat pumps have lower emissions in many locales today, and as the electricity fueling a heat pump becomes cleaner over time, emissions fall relative to the heat produced. The United Kingdom and other European countries have adopted policies to implement clean heating that rely in large part on electric technologies, either directly through heat pumps or indirectly through clean production of hydrogen.



Today, electricity provides a cleaner fuel option for an array of applications across the economy. As the electric system becomes even cleaner, electrification becomes an even more attractive path for reducing the economy's environmental footprint, while keeping energy services affordable. Electrification's economic and environmental benefits are evident from studies examining energy services comprehensively. Based upon hundreds of published scenarios produced by dozens of models around the world,¹⁴ the United Nations' Intergovernmental Panel on Climate Change (IPCC) has concluded that decarbonizing electricity coupled with accelerated electrification is a "key component" for cost-effective, deep cuts in global emissions. The European Commission's detailed examination of climate policy for Europe, *Energy Roadmap 2050*, projects a near doubling of electricity's share of "final energy" from 20% today to 36-39% in 2050.^{15, 16} Edmonds, et al., in one of the few papers to examine electrification in detail globally and regionally, concluded the tighter the carbon constraint, the greater the role of electricity—even with very conservative

¹² See for example, *The Third Wave of Energy Efficiency*. EPRI 3002009354. November 2016.

¹³ Key assumptions underlying these calculations include: Gasoline at \$3/gallon retail; electricity at \$100/MWh; 30 mpg and 0.08 tons CO₂/mile for the gasoline vehicle; 300 Wh/mile and 0.3 tons CO₂/MWh (consistent with modern gas-fired turbines) for the electric vehicle.

¹⁴ IPCC, 2014: *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

¹⁵ Electricity's share of final energy is one metric used to provide an aggregate, quantitative measure of electricity's role in the energy system. Electricity's role has grown over the last century largely driven by increased use of electricity-dominated end-uses, e.g., lighting, air conditioning, home

ELECTRICITY'S SHARE OF TOTAL ENERGY CONSUMPTION, BY SECTOR 1949-2015 (SOURCE: EIA AER 2016)

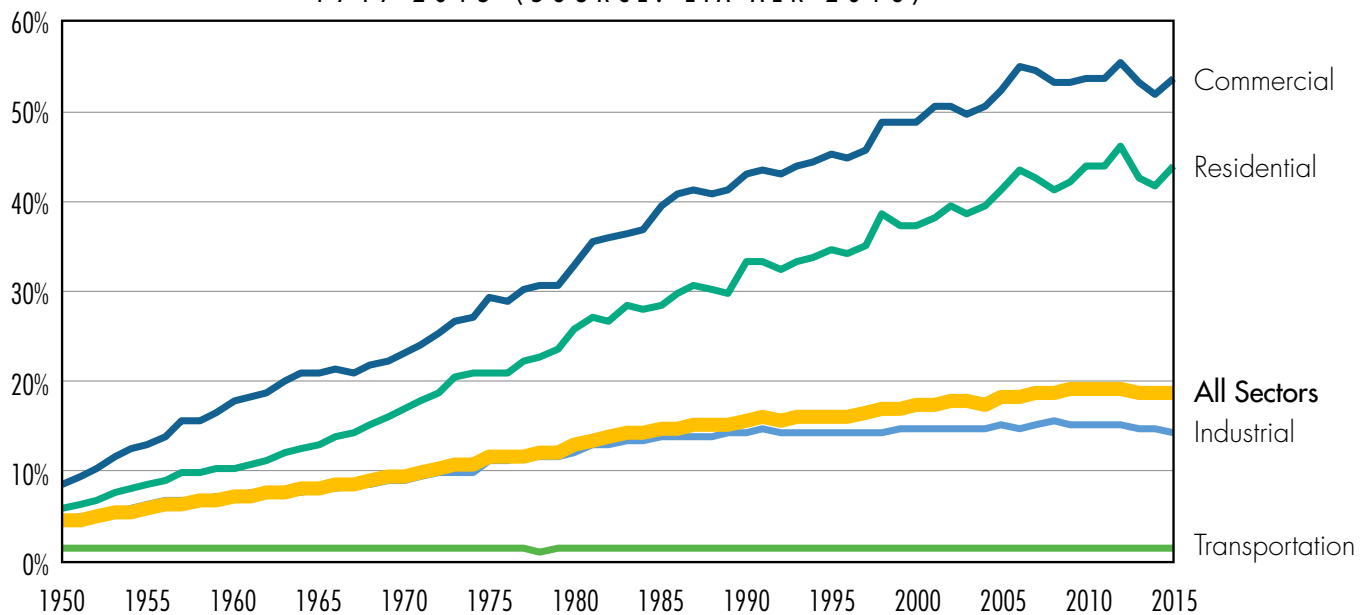


Figure 2. Electricity's share of energy use and its role have grown steadily, rising from 3% of final energy in 1950 to 18% in 2015. This growth has been led by the residential and commercial sectors where electricity has supplied increasing and changing demands for light, cooling, entertainment, and information/communication. Electricity's growth also has been significant in the industrial sector, until a recent drop driven by lower natural gas prices. For U.S. transportation, electrification—primarily rail and light-duty vehicles—has been negligible. To date, this growth has been led by increased demand for end-uses where electricity dominates. Those trends are expected to continue and be supplemented by technology- and policy-driven electrification.

assumptions regarding improvements in power generation technology.¹⁷ Other EPRI research consistently supports this conclusion.¹⁸ There are many ways to cut emissions, but these studies underscore that, both for specific and very broad application, electrification is crucial to making emission controls cost-effective and affordable.

Recent EPRI analyses illustrate how electrification may accelerate in the United States and reduce transport emissions, even without prescriptive environmental policies.¹⁹ Figure 2 provides context for these analyses. While the commercial and residential sectors have steadily electrified since 1950, and industry has electrified somewhat, U.S. electricity use for transportation has remained negligible. The U.S. Energy Information Administration, in the reference case in its

2017 Annual Energy Outlook, sees this trend continuing with electricity growing from 0.1% of delivered transport fuel in 2015 to only 1.5% in 2050.²⁰ In contrast, EPRI analyses suggest that automobiles and other light-duty vehicles may be poised for rapid electrification as prices drop, capabilities increase, and manufacturers expand offerings. For example, the plausible achievement of purchase price parity between electric and gasoline vehicles by 2025²¹ could increase electricity's share of transport and overall final energy markedly over the next fifteen years—yielding new electric loads and local challenges for distribution and transmission infrastructure coupled with significant new opportunities for managing load and the electric system flexibly.

appliances, communication, entertainment. Electrification – defined here as switching from fossil fuel end-uses to electric ones driven by technology advances or efficiency/environmental goals – appears poised to accelerate this growth.

¹⁶ European Commission: "Energy Roadmap 2050", European Commission, 2011.

¹⁷ Edmonds J. A., T. Wilson, M. A. Wise, and J. P. Weyant (2006). Electrification of the Economy and CO₂ Emissions Mitigation. Environmental Economics and Policy Studies 7, 175 – 203.

¹⁸ Rose S., R. Richels, G. Blanford, and T. Rutherford (2016). "The Paris Agreement and Next Steps in Limiting Global Warming."

¹⁹ IEN Electrification white paper forthcoming, June 2017.

²⁰ Energy Information Administration's Annual Energy Outlook 2017.

²¹ Projections of potential cost parity between electric vehicles and internal combustion in the next decade are emerging from a variety of sources. EPRI's internal analysis, which updated US-DOE automobile cost simulations with more aggressive assumptions about battery improvements, suggested purchase price parity for EVs without subsidies in the 2020s. The Wall Street Journal stated, "Mercedes-maker Daimler thinks the production cost of engine and battery technology might reach parity in 2025. But the tipping point for consumers, who also factor in subsidies and running costs, will

Vehicle electrification can lead to much more than cost saving, efficiency gains, and CO₂ emissions benefits. Jointly with the Natural Resources Defense Council, EPRI concluded that "...widespread use of electric vehicles—including lawn and garden equipment and heavy industrial equipment such as forklifts—could radically improve air quality, particularly in densely populated urban areas..." (see Figure 3).²² In recent years, substantial attention has been directed to electrification as a means of cutting global CO₂ and other greenhouse gas emissions. But findings that electrification can lower local and regional pollutants underscores how both policymakers and consumers can look to electrification to address an array of pollution reduction goals.

Creating technologies that enable more efficient provision of energy services does not by itself make energy systems cleaner. Public policies can offer additional incentives that alter customers' decisions and those made by the energy sector businesses that serve them.

Expanded customer choice, increased efficiency, and the advantages of electrification will not be achieved without effort. They require investment in innovation and testing new ideas, along with complementary policies and the creation of markets, such as those that empower customers to choose cleaner, affordable energy systems. These key actions are summarized in the box on the following page.

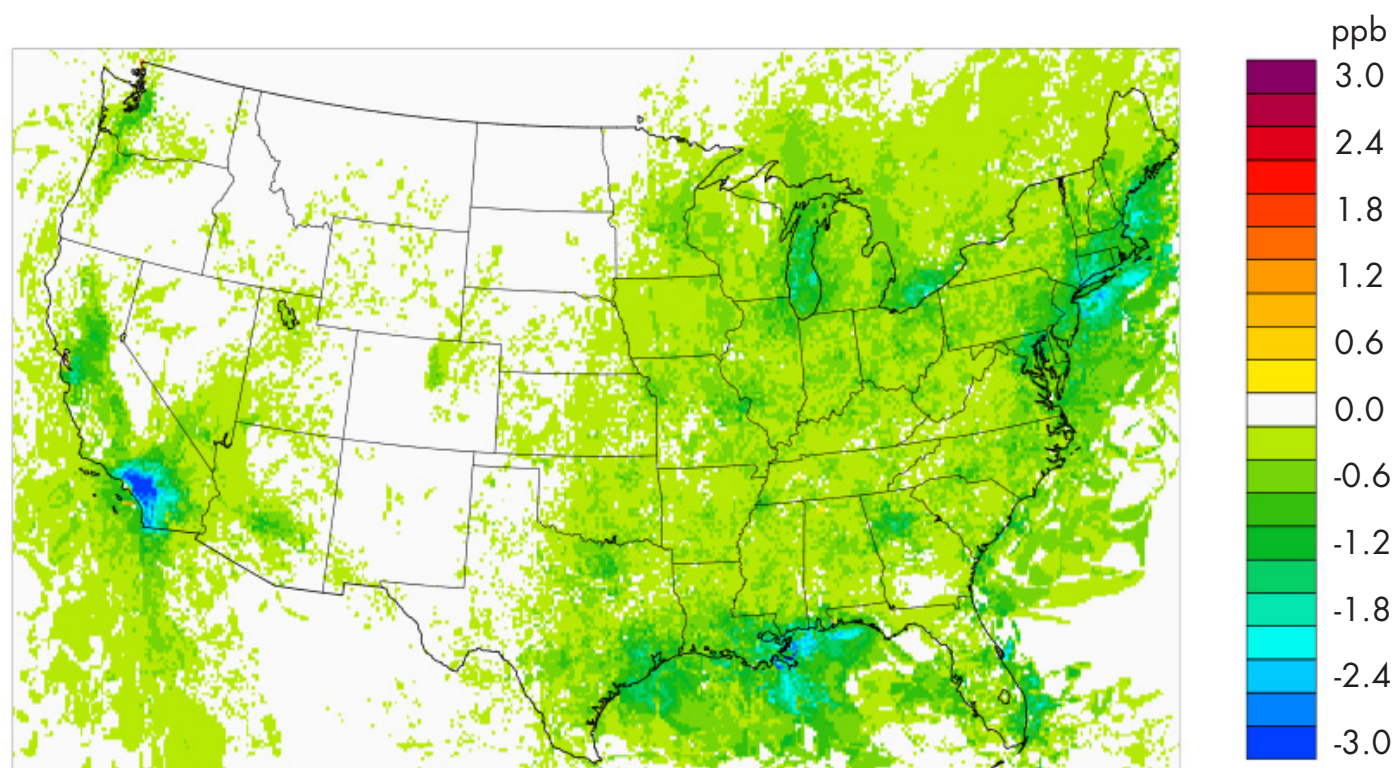


Figure 3. Reductions in ozone due to electrification (results for 2030; based on fourth highest daily max eight-hour ozone concentration).

be earlier" in the article, *Investors Get Ready for the Coming Electric Car Revolution*, December 13, 2016. In its February 25, 2016 report, *Global EV Sales Outlook to 2040*, Bloomberg New Energy Finance projected "By 2022, the unsubsidized total cost of ownership of BEVs will fall below that of an internal combustion engine assuming oil is between \$50 and \$70 per barrel."

²² Reference... <http://epri.co/3002006881>).

KEY ACTIONS: *Using Affordable, Cleaner Energy – Through Efficiency and Electrification*

Policy, regulation, and technology advances are required to promote energy efficiency and to enable or encourage electrification:

- ***Explore technical options and policies for achieving cost-effective efficiency gains.*** Traditional energy efficiency efforts should expand to look beyond equipment improvements to examine broader gains from fuel switching (gas furnace to heat pump) and process improvement (e.g., airlines reduce energy use per passenger using price structures to fill seats). Efficiency metrics that assume two-thirds losses in all electricity generation are becoming inappropriate in many regions. Regulators can review efficiency policies to assess and improve their effectiveness.
- ***Evaluate energy and environmental policies and regulations that allow or encourage electrification.*** Understand how each sector's policies drive disincentives or work at cross-purposes for efficient, effective compliance throughout the energy sector. Examples include rules that penalize electric utilities for increasing emissions as a result of powering large fleets of electric vehicles, despite a net reduction in emissions when considering the gasoline use that is displaced. Research must provide for accurate accounting of electrification's net results and identify approaches to overcome financial, ownership, and informational impediments. Policymakers and regulators can seek new cross-sector approaches to achieve their goals and create incentives necessary to spur infrastructure investment (e.g., electric vehicle charging structure).
- ***Develop and demonstrate advanced, highly efficient, clean-energy end-use technologies.*** EPRI deems it necessary to identify promising electric technologies and develop those that drive and serve new customer preferences and that provide increased value as economics and policies evolve. Continued investment in these technologies can reduce emissions per unit of energy services, reduce water consumption and other environmental impacts, and offer customers an array of benefits including lower cost, productivity gains, improved product quality, and a cleaner, safer work environment. Also important are advances in fuel cells and other technologies for consuming cleanly produced hydrogen as well as technology, communication protocols, and distribution standards for effectively integrating these end-use resources in the system. Sustained funding for research and technology demonstrations are critical to keeping promising products in the pipeline.

PRODUCING CLEANER ENERGY – THROUGH MORE EFFICIENT, ENVIRONMENTALLY SUSTAINABLE, AND FLEXIBLE GENERATION

Electricity produced from cleaner resources such as renewable energy, nuclear power, and fossil-fueled generation with carbon capture offers the potential to reduce energy systems' emissions substantially. With technology advances in both utility-scale and distributed generation, the cost of cleaner energy declines substantially. Current opportunities and issues for each power source include:

- Solar and wind offer variable power production and plummeting equipment prices, with further decreases likely. To address day-to-day variation in supply, grid operators use forecasting to schedule reserves from flexible resources (primarily thermal generation today) with an increasing role for demand response and energy storage. Expanded transmission can also connect large regional centers of diverse supply with load centered in other regions. Seasonal variation in production may be much more expensive to address and require well-functioning capacity markets and backup generation as well as innovation and deployment of long-term storage.
- Nuclear power's track record emphasizes reliable, baseload power production with essentially zero emissions. However, it can take many years to build in the United States and Western Europe, making financing a challenge and payback uncertain. Significant nuclear power development is proceeding in nations such as South Korea and China, where plants are constructed faster and at lower cost; construction experience is enabling companies in these countries to emerge as equipment vendors and operators for other countries. Existing nuclear plants also face challenges. An economic challenge arises in electricity markets with systemically low and negative energy prices—a condition that often accompanies surging or sustained oversupply of renewable generation at zero marginal cost. This market challenge has been exacerbated in the United States by persistent low natural gas prices (\$2-3/MMBtu).²³ Public acceptance offers ongoing challenges—evident with the planned closing of all German nuclear plants and the suspended operation of nearly all Japanese plants post-Fukushima. Ad-



vanced plant designs and ongoing R&D in support of operating plants offer enhanced approaches to address these issues.

- Carbon capture, transport and utilization and storage (CCUS) are generally considered essential to making deep cuts in global CO₂ emissions. The idea of CCUS has been around for a long time, but sustained investment to develop and demonstrate these technologies has lagged. Beneficial use of captured CO₂—such as for enhanced oil recovery or some industrial processes—offers attractive niche applications to introduce and establish these technologies. Combined with biomass, CCUS may be viable for removing atmospheric CO₂—in effect, creating power plants that offer useful energy services (electricity) with negative net emissions. This combination plays a key role in theory, appearing as a critically important technology in almost all modeling studies of low-carbon futures, but has yet to attract significant investment. The challenges with CCUS are partly technical and mainly, it seems, linked to the lack of viable business models and regulatory frameworks necessary to attract investment.

²³ The states of New York and Illinois in late 2016 implemented policies to help keep their nuclear plants running; several other states and possibly the federal government are considering similar policies.

These three technology clusters will be important in most regions. Other important technologies will depend on geography and markets. For example, in the United States and other countries with abundant, low-cost natural gas, this fuel likely will account for a growing share of relatively lower-carbon power for decades to come. The switch from coal to natural gas-fired power generation has reduced emissions over the past decade. Prospectively, low natural gas prices could continue the trend. Natural gas also may fuel a significantly larger portion of the mid- to heavy-duty vehicle fleet, based on economics and environmental benefits. The future for natural gas, however, depends on continued advances in production combined with environmental policy choices, such as whether society seeks emission cuts so deep that conventional gas technology can't deliver. Renewable natural gas produced from landfills, dairy operations, and other sources could help further decarbonize this fuel, making it instrumental in a transition to much lower emissions. Cost-effective CCUS combined with natural gas also could be important—especially if coupled in a manner to efficiently provide the variable output needed to help integrate renewables with the power grid.

Energy diversity has value

For the foreseeable future, the drive to create cleaner energy carriers will focus on electricity. However, any comprehensive consideration of energy system transformation must consider unknowns regarding which energy carriers will best serve varied energy needs. Hydrogen, like electricity, can be a carrier (or transmitter) of cleaner energy. A central question for its future as a clean energy carrier is where it will complement versus substitute for electricity. Today, almost all hydrogen use is in industrial applications with limited use for heavy transport (e.g., buses). The predominant processes for creating hydrogen today also produce significant CO₂ emissions. Clean hydrogen production costs are at present economically prohibitive, and no clear path has emerged for cost-effective delivery at large scale or developing safety standards for public use. Still, the Integrated Energy Network pathway will consider using hydrogen to store surplus renewable or nuclear electricity and as an energy carrier for certain industrial and transport applications. For residential or commercial use, cleanly produced hydrogen might be blended with natural gas to lower the natural gas supply's carbon content—making it possible for societies to reduce emissions while using the existing natural gas network.

Because many unknowns remain—even with the most prom-

ising choices for cleaner production of electricity—substantial research by EPRI and others has examined the value of a diversified, full portfolio of technology options. The IPCC emphasized this by noting that efforts to decarbonize energy could be many times more expensive if attempted without the full portfolio—notably (in order) CCUS, renewables, and nuclear. Indeed, the overarching imperative for integrating energy systems may well require a concerted drive to a diverse portfolio. Integration creates more opportunities to arbitrage and diversify risk across a larger and more capable energy system.

Key challenges for producing cleaner energy include making advances in individual technologies, improving systems' flexibility to manage variable production effectively, and creation of policies and regulation to support full-scale technology demonstrations. An essential foundation for this is demonstrating through research and development the value of a full portfolio of technologies.

KEY ACTIONS: *Producing Cleaner Energy*

In working across the energy sector, a clear priority is to refine and deepen a common understanding of the opportunities and challenges inherent in each energy resource and system:

- ***Develop a better understanding of renewable energy integration challenges, and inform policy, regulatory, and business models.*** Policy, business model, and technical approaches must progress in concert to realize the full benefits of variable renewable production. An integrated portfolio of technologies should be explored for dealing efficiently with daily and seasonal variability. This includes improved use of forecasting, expanded long-distance transmission, diverse storage options, and demand response. Market, regulatory, and communication and controls advances are required to enable and sustain the system's efficient, reliable operation as variable resources are added. Environmental research is needed to anticipate and address emerging environmental issues associated with these technologies.
- ***Create advanced renewable technologies.*** Next-generation renewable technologies that can respond to grid and market conditions more rapidly and reliably are essential to reduce costs further and increase capabilities to operate more efficiently as part of the overall system.
- ***Demonstrate advanced low-emission fossil technologies and the policies, regulations, and business models needed to support them.*** Research is essential on advanced power cycles and on carbon capture, storage, and utilization. Support for demonstrations is needed for capture technologies at scale; basic research is needed to examine use of CO₂ captured, and regulations are needed to deal with underground storage.
- ***Support development of new nuclear designs and the policies, market reforms and business models needed to support existing and new nuclear.*** Advanced reactor designs and government policies are needed that support development of new plants and continued operation of existing plants.
- ***Explore bioenergy technology options, particularly bioenergy with CCUS.*** Bioenergy with CCUS is assumed to be deployed widely in most scenarios that achieve the long-term goals of deep carbon reduction, (e.g., the goals of the Paris Climate Agreement). Research must address many questions regarding the production and control technologies and sustainable, large-scale, low- or no-net-emission fuel supplies, including attention to feedstocks and life-cycle emissions accounting.
- ***Explore the role of hydrogen as a clean carrier of energy and the economic and policy impediments to its development.*** Research must focus on producing hydrogen cleanly, on business models for developing a hydrogen infrastructure, and on safety.
- ***Explore flexible operation opportunities for all generation technologies.*** R&D should be undertaken addressing aspects or features of the technologies above that support variable power generation through fast ramping, advanced inverters, long-term storage, or other technology. An increasingly flexible central station fleet is a key enabler of the Integrated Energy Network.

INTEGRATING ENERGY RESOURCES – THROUGH NEW CONTROL TECHNOLOGIES AND MARKETS

The systems and infrastructure for supplying electricity, gas, and water are increasingly interconnected and interdependent. However, the flows of information and market signals to control systems are minimally integrated across these sectors as are the impacts of these systems on the natural environment. Such fragmentation increases costs, limits customer choice, and exacerbates vulnerability relative to a more fully integrated system.

Improvements in electric systems controls, coupled with advances in protocols, cyber security, application program interfaces, and telecommunications will make it possible to integrate distributed generation seamlessly into the grid and improve system productivity and flexibility. Also, decisions regarding energy and other natural resources can be considered in real time, enabling gains in affordability, reliability, efficiency, and expanded customer choices. Digital technologies provide new opportunities for choice, control, and optimization in sectors, and ultimately, coordinated operation among sectors. The electric sector is well ahead of the others in implementing these technologies and is positioned as an essential enabler and backbone of the



Integrated Energy Network. Figure 4 highlights some of the key components and connections in the Integrated Energy Network with electricity as the keystone.



Figure 4. The electric, gas, and water systems are interconnected and interdependent. Electricity, gas, water, data, and thermal (heat and cold) flow through a highly-connected, centerless system. The Integrated Grid in the electric sector provides a physical and logical platform for beginning to integrate these existing systems as well as potential future energy systems, such as electric transport and hydrogen.

Building the Integrated Grid is a key first step

Near-term, a critical step in the Integrated Energy Network's pathway is the effective integration of the bulk electric grid with the many new distributed energy resources, a challenge EPRI refers to as the Integrated Grid.²⁴ The resulting shift to more variable supply and demand characteristics—along with improving energy storage technologies and markets for demand response—will force a shift from the traditional methods for forecasting load and dispatching generation that were developed and honed over decades of operating large, centralized grids. Currently, most electric power systems still operate through “forecast and supply” methods that ramp up and down the controllable resources to deal with demand that is treated as variable and passively unresponsive. Integration increasingly requires a new “forecast and balance” approach through which both load and generation are forecast while supply and demand technologies are used to balance the system, often through market signals. Integrated planning for generation, transmission, and distribution systems (loosely linked until recently) can equip utilities and customers to make better use of all resources.

Achieving this requires expanding and upgrading the electric grid. Most transmission assets were designed to move power from conventional generation (sited for access to water and fuel) to distribution systems within utility service territories. The rapid deployment of renewable energy and the closing of existing generation assets changes power flows dramatically and puts pressure on an aging transmission infrastructure. Near term, this requires inspection, assessment and monitoring, and upgrades to maintain reliability. Further, it necessitates regional transmission expansion to connect generation from different locations. Because renewable resources (e.g., wind, solar) centered in different locations provides operational diversity, the value of transmission systems increases as they are able to link these resources with centers of load over much larger areas, while using more sophisticated, comprehensive control systems.

Integrating electricity, natural gas, transportation, and water systems offers new opportunities

Making the electricity system more capable is just the start. In regions where the electric sector's reliance on natural gas is growing, further integrating electricity and natural gas networks can offer substantial value. While electricity generation is increasingly dependent on natural gas, the natural

gas supply system itself often relies in part on electricity to power compressor stations and control the transport of natural gas. Similar intersections exist with product demand where customers depend on natural gas and electricity in tandem to provide energy services. When natural gas supply is constrained—for example, during periods of extreme cold with high heating demand for natural gas—it may be impossible to provide heat and electric services that are reliable simultaneously. Better integration of planning as well as dispatch and markets can give customers and operators more flexibility when faced with difficult choices.

Even greater potential for integration lies with services that, traditionally, were not the province of the electric power industry. In the coming decade, integrating vehicles into an electricity-focused network can create new needs for investment and infrastructure control. The deployment of significantly more electric vehicle charging stations can require upgrades to the electric distribution and regional transmission systems. Also needed will be new technology standards and business models that balance the need for predictability with fundamental uncertainties resulting from rapidly changing technology, markets, and consumer tastes. From a system perspective, these new loads can help optimize a system operating with substantial variable generation. For example, charging electric vehicles in the afternoon in regions with high solar penetration could enable a more efficient deployment of additional solar. With electric vehicle batteries sufficient in number to supply meaningful power to the grid, this value increases further. To effectively incorporate electric vehicles and electricity storage into the grid requires that it be integrated with information and communications technologies to enhance monitoring, measurement, and control and that systems are created that are interoperable, more dynamic, automated, and reliable.

Looking further into the future, opportunities abound with the integration of energy services and natural resources. Electricity and water supply systems are inextricably tied. Water is essential to thermal generation of power, the dominant source of supply today; electric power is widely used to produce, move, and purify water. As water supplies come under more pressure, the electric and energy industries must use it sustainably. On the demand side, energy-water interactions take on increasing importance as storage of water heat and other water uses have the potential to offer some flexibility to electric system operations.

²⁴ For resources on EPRI's Integrated Grid initiative, see <http://integratedgrid.com>.

Resilience and security are essential

A central challenge with automation and integration is to deploy resilient, integrated systems that are not prone to cascading failure. Bigger networks are not inherently more secure unless they can better identify and contain failure, and perform “self-healing.” Physical and cyber threats to the energy system are real and increasing, and the public has become attuned to how pervasive digitalization can affect privacy. Each energy and water network is susceptible to disruption, and through physical network interconnections, a problem or its consequences in one can affect all. It is critical that information integration strengthens capabilities to localize, control, and overcome such threats, making integrated systems the more reliable alternative.

Other challenges to integration span technology, policy, regulatory, and standards domains. Key actions are listed in the box on the following page.

KEY ACTIONS: *Integrating Energy Resources*

A first step is to create a robust, secure Integrated (electric) Grid to efficiently integrate central and distributed electric resources:

- ***Develop interconnection rules and communications technology and standards.*** Rules and tools are needed to support real-time data transfer and to address privacy. This requires technology development and standards development along with regulatory and policy support.
- ***Assess and deploy advanced distribution and reliability technologies,*** including smart inverters, distribution management systems, sensors, distributed energy storage, and demand response – and the communication and information technology infrastructure to tie them together. Regulatory support is needed for testing and demonstrating promising technologies.
- ***Create strategies for integrating distributed energy resources with grid planning and operation*** for efficient and effective system planning and operations. Efficient investment and operation of the electric grid require broad, specific coordination across customer, distribution, transmission, and generation planning functions. This requires new tools and processes for companies as well as regulatory support.
- ***Inform policy and regulation development to enable flexible yet reliable operation of the electric system for effective DER integration*** reflecting the costs and benefits of the various components and systems. Much remains to be done for providing detailed assessments and for determining costs and benefits of electric system components. Fundamental challenges include: value depends on location and on what else is connected, with the result that value will change over time.
- ***Strengthen and expand the transmission system to maintain reliability and enable more flexible operation.*** Inspection, assessment, monitoring, and investment are needed to ensure transmission system reliability, given rapid changes in electric generation technologies and locations. Transmission system expansion will enable integration of variable generation and loads and will be essential to support electrification. New “lower-impact” substation and line designs are among the technologies needed to increase public acceptance, reduce costs, and maintain reliability.

As the Integrated Grid develops, it becomes instrumental in developing and applying comparable smart technologies for natural gas, water, and other systems. While these systems’ needs differ, they have much in common with respect to sensors/meters/switches, communication, data analysis, and cyber security architectures. They can be made interoperable through development of an architecture, operational principles, and procedures that include data format and communications systems.

- ***Identify ways to integrate systems as they are automated for production, delivery, and use of electricity, natural gas, and water.*** Common elements among devices, architectures, and software may support and drive common interests, approaches, and solutions.
- ***Assess key interfaces between gas and electric systems and markets; explore market integration.*** Include comprehensive consideration of environmental challenges and opportunities, integrated modeling of operations and planning, and market integration to achieve efficiency.
- ***Assess key interfaces between energy and water*** to enable efficient water use, support more flexible operation of the electric system, and improve environmental performance.
- ***Develop diverse capabilities for managing, assessing, and analyzing “big data”*** to meet the future energy system’s dynamic, real-time requirements.

KEY ACTIONS THAT CROSS BOUNDARIES

With respect to using cleaner energy, producing cleaner energy, and integrating energy resources, the Integrated Energy Network pathway must be considered from technological, economic, and social perspectives. Important social considerations such as security and privacy will be integral to progress along the pathway and in demonstrating the

value of broader integration to diverse social groups and interests. Environmental issues must be anticipated and addressed, and worker safety ensured as the energy system changes. With these perspectives in mind, the actions below cross traditional boundaries to support broader recognition of the opportunities and challenges presented by IEN.

KEY ACTIONS That Cross Traditional Boundaries

Actions relevant to all three IEN elements:

- ***Develop a framework for evaluating the costs and benefits of integration.*** An essential step to guide investments in coordinating and integrating energy and natural resource systems is a comprehensive framework for assessing costs and benefits. The Integrated Grid benefit-cost framework provides a starting point, but much more thought is needed.
- ***Inform policy/regulatory decisions and customer choices with clearly communicated scientific and technological findings and perspectives.*** Understand the consequences of consumer actions and choices, based on a comprehensive analysis of impacts and benefits with respect to cost, reliability, and other factors such as air/water emissions, waste, and land use.
- ***Anticipate and address emerging environmental and worker safety issues.*** The IEN pathway creates substantial change in how energy is produced, transported, and used. It is essential to anticipate and address effectively emerging environmental and worker safety issues (e.g., environmental impacts of renewables).
- ***Implement funding mechanisms and processes to support development and demonstration of new technology.*** Allocate resources nationally and regionally sufficient to support development and demonstration of technologies at commercial scale. Development at less-than-commercial scale leaves too many unknowns with respect to cleaner energy production, delivery, and use. Pursue broader public-private collaboration to secure adequate funding.
- ***Expand and coordinate international and cross-sector research.*** International and cross-sector coordination of research, development, and demonstration of technologies is key to efficient, timely progress in development and deployment.
- ***Focus on security, reliability, resiliency, and privacy.*** Public acceptance depends on effective, concerted attention to cyber security and privacy controls in moving to a more integrated, digitally controlled energy system.
- ***Expand public education and communication.*** For over a century, the inner workings and complexities of the electric system have been largely hidden from the public, whose concern primarily focuses on whether the lights come on at the flip of the switch. As customers become more active in managing energy use, education is needed help them understand the system and their options.

INTEGRATED ENERGY NETWORK—THE PATH FORWARD

The Integrated Energy Network pathway outlines EPRI's view of first steps to an efficient, reliable, affordable, and cleaner energy future. Such a future is plausible but not assured. As highlighted in this introduction, the IEN pathway requires advances in science, technology, markets, policy, regulation, business models, and customer awareness.

At its essence, the IEN calls for a change in how we think about energy:

- It argues for a much more integrated approach to providing energy services and managing natural resources—a fundamental shift from the planning, operation, and regulation of these systems today.
- It leverages digital technologies that enable levels of integration that would have seemed implausible even a few years ago.
- It requires that technology, policy, regulation, and business models must advance in concert if the Integrated Energy Network is to be realized.

Next steps

In the preceding sections, EPRI described key actions in the IEN pathway. Going forward, EPRI will initiate and inform discussions that address all aspects of the IEN, including technology, policies, regulations, standards, economics, and market frameworks.

The IEN website, <http://IEN.EPRI.com>, will provide an ongoing slate of EPRI research programs, research and discussion papers, workshops, collaborations, and other opportunities to get involved. EPRI plans to release more detailed characterizations of each IEN pillar and invites comment and input as they are developed:

- *Producing Cleaner Energy*, spring 2017 release
- *Using Affordable, Cleaner Energy*, June 2017 release
- *Integrating Energy Resources*, August 2017 release as part of a complete IEN paper

Supplementing these will be technical white papers that examine: generation technology costs; perspectives on electrification opportunities, challenges, and actions needed; the dimensions of energy-water interactions; cyber security in an Integrated Energy Network; an Integrated Energy Network Planning white paper that examines the new challenges of utility planning; and perspectives on a framework for estimating costs and benefits on the IEN.

As 2017 progresses, EPRI will announce new collaborations and R&D to consider near-term and long-term steps along the Integrated Energy Network pathway.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, affordability, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI members represent 90% of the electric utility revenue in the United States with international participation in 35 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

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