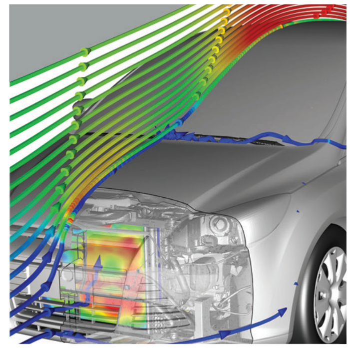
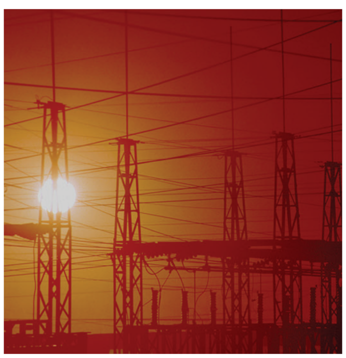
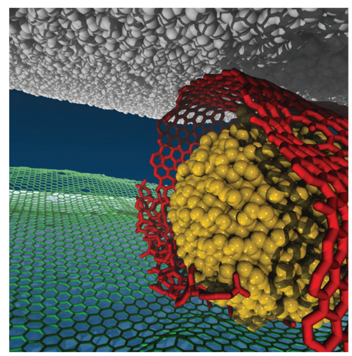


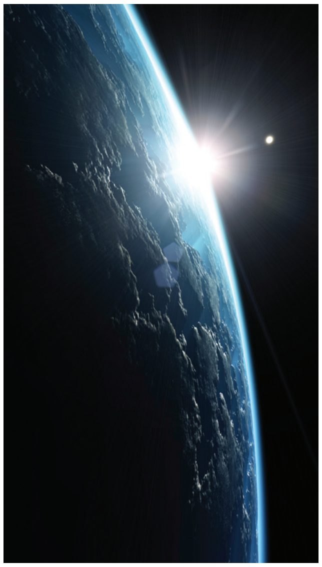





QUADRENNIAL TECHNOLOGY REVIEW

AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES

Chapter 11: Summary and Conclusions
September 2015



Issues and RDD&D Opportunities

- Four overarching themes in energy technology research, development, demonstration, and deployment (RDD&D) are identified:
  - Energy systems convergence
  - Diversification within the energy sectors
  - Energy efficiency everywhere
  - Confluence of computational and empirical capabilities
- Six sets of core opportunities for specific RDD&D activities are presented, organized by the energy sectors represented in the technical chapters of this report:
  - Enabling modernization of electric power systems
  - Advancing clean electric power technologies
  - Increasing efficiency of building systems and technologies
  - Innovating clean energy technologies in advanced manufacturing
  - Advancing systems and technologies to produce cleaner fuels
  - Advancing clean transportation and vehicle systems and technologies
- Twelve crosscutting technology areas are identified:
  - Electric grid modernization
  - Systems integration
  - Cybersecurity
  - Energy-water nexus
  - Subsurface science and technologies
  - Materials
  - Fuel/engine co-optimization
  - Energy storage
  - Computational modeling and simulation
  - Data and analysis
  - Analysis of complex systems
  - Characterization and control of material at multiscales

11 Summary and Conclusions

11.1 Introduction

To meet our nation's strategic energy objectives of a secure, competitive, and environmentally responsible energy system, broad deployment of a range of advanced energy technologies will be needed. The 2015 Quadrennial Technology Review (QTR) examines the status of various technologies and systems from six core energy sectors as well as the research, development, demonstration, and deployment (RDD&D) opportunities to advance them. More than fifty technology assessments were performed that examined in great depth RDD&D opportunities for those technologies within each sector. The increasing interconnectedness and interdependency among energy sectors necessitated an energy system perspective as the identified RDD&D opportunities were examined.

By approaching these reviews from an energy system perspective, four overarching themes emerged.

The first of these themes is the convergence of energy systems**.** Virtually all sectors of the energy system are becoming more interdependent. Information and communications technologies, advanced sensors and controls, and market phenomena are enabling the proliferation of advanced technologies that overlap the power generation, electricity transmission and distribution, buildings, manufacturing, fuels, and transportation sectors. Furthermore, energy systems are increasingly coupled to water systems, material flows, waste products, and financial markets. Properly tuned and integrated systems have the potential to improve their overall operations, increase their efficiencies, and enable fundamentally new concepts in the structure of the economy and urban environments. Across all sectors, RDD&D opportunities for understanding, predicting, designing and controlling complex and integrated energy systems were identified.

The second theme is the potential of increased diversification of energy resources, carriers, and uses. The QTR found that many energy sectors in the United States have the opportunity for multiple technology pathways and the potential of increased diversification. This diversification creates challenges to energy infrastructures. In transportation, recent increases in electric vehicle offerings and new developments in fuel cells complement existing alternatives to petroleum such as (natural) gas and biofuels, but complicates refueling infrastructure. In the power generation sector, retiring units are being replaced with a mixture of natural gas, wind, and solar generation, among others, increasing the complexity of electric grid management. Diversification can also be advantageous by giving our energy system resource flexibility and consumer choice. These multiple resource options can potentially have stabilizing effects on the marketplace and enhance energy security.

The third theme is improve efficiency everywhere. Energy efficiency has a long and well-established record of success in reducing energy use, as well as associated factors, such as water use and waste generation. Efficiency improvements can significantly benefit national security, the economy, and the environment, for example, by reducing oil use, business and consumer costs, and environmental emissions, respectively. In the past four decades, energy efficiency together with structural change has increased the energy productivity of the U.S. economy from $75 billion per quad in 1975 to about $160 billion per quad today, both in chained 2009 dollars.

RDD&D opportunities to advance cost-effective efficiency technologies abound throughout all energy sectors and systems. The delivery of energy services typically goes through a sequence of energy conversion steps from the initial energy resources to the final delivered energy services, each with associated energy losses. Improving efficiency at any step in the energy services chain can proportionately reduce the energy use and associated losses at each of the upstream steps. Energy efficiency can thus provide high leverage in reducing energy use and cost.

The fourth and final theme is the growing confluence of computational and empirical capabilities that is enabling a new era of "systems by design." This confluence includes scientific theory, modeling, simulation, high-performance computing, data management and analysis, algorithms, software, and high-throughput experimental techniques to enable the prediction, design, engineering, and experimental characterization of materials and systems from the atomic through the nano-, meso-, and macroscale to manufacturing. These capabilities offer the potential to develop new materials, technologies, and systems more rapidly and at lower cost than traditional approaches. An example is the multiagency Materials Genome Initiative (MGI), launched in 2011, which has the development of such capabilities as its central focus. Federal user facilities and computational facilities as described in Chapter 9 make advanced scientific tools available to energy technology developers.

These themes are found across sectors and throughout the broader energy system. Within this complex "system of systems," RDD&D opportunities and a set of twelve crosscutting technology areas (see Section 11.8) that are attuned to these themes are essential to achieving the nation's energy goals. Sector-specific opportunities are summarized in textboxes on subsequent pages.

11.2 Enabling Modernization of the Electric Power System

Fundamental changes in both supply and demand technologies are placing new requirements on the electric power system. On the supply side, there is a diversification of resources as aging, low-efficiency capacity is replaced by a mix of central stations and distributed generation, powered by a mix of fossil and renewable resources. On the demand side, diversification includes a rapidly growing use of distributed generation and interactive control systems in buildings, industrial equipment, and consumer goods.

Accompanying these changes is a convergence of digital communications and control systems ("smart grid" technologies) to improve performance and engage consumers. Additionally, grid operations are moving from directing systems with a handful of control points at central stations to ones with potentially millions of highly interactive distributed control points.

These trends create new technical requirements for a grid that is more flexible and agile, with the ability to dynamically optimize grid operations in near-instant time frames. (See textbox: *RDD&D Opportunities for Enabling Modernization of Electric Power Systems.)*

11.3 Advancing Clean Electric Power Technologies

The current portfolio of electricity generation technologies is diversifying and improving in efficiency through a combination of reliable, but aging, base-load generation, increasing use of renewable resources, and new generation plants that use the significant domestic natural gas resources.

As the industry evolves to meet growing electrification and greenhouse gas (GHG) emissions reduction goals, challenges arise in optimizing this system, minimizing risks, and maintaining reasonable cost. Progress will consist of advancements in

RDD&D Opportunities for Enabling Modernization of Electric Power Systems

The modern grid needs enhanced observability, controllability, and interoperability to effectively deal with the burgeoning complexities of generation and end use. Key opportunities include the following:

- Advanced sensing, modeling, and controls to support this transformation
- Development of next-generation materials and component designs for power electronic systems and energy storage

Security, flexibility, agility, and resiliency will be essential outcomes. The design and operation of the electric power system will need to accommodate the shift from a hierarchical, centrally-controlled system to a much more distributed system; from a deterministic system to a more stochastic system; from a system with one-way power flow in distribution to a system with bidirectional flows; from a unidirectional system to a more networked system; and from a system with passive loads to one with numerous interactive and dynamic loads.

Changes in operational characteristics help define the research and development requirements of modern electric power systems, improve performance, lower costs, and address our national energy challenges. RDD&D opportunities include:

- Develop and refine grid architectures and new system designs
- Develop software and visualization tools for enhanced, real-time operations and control of the transmission and distribution grid
- Develop transmission and distribution component designs for higher performance, reliability, and resilience
- Embed intelligence, communication, and control capabilities into distributed energy resources and microgrids to support grid operations
- Improve energy storage and facilitating integration
- Develop power system planning tools
- Design systems to improve physical and cybersecurity of the grid

technologies currently deployed, such as more efficient, fossil-based generation with carbon capture or advanced nuclear reactors; rapidly advancing renewable technologies, including wind and solar energy; and technologies on the horizon, such as fuel cells and marine hydrokinetic power. For details on RDD&D opportunities, see textbox: *RDD&D Opportunities for Advancing Clean and Cost-Competitive Electric Power Technologies.*

11.4 Increasing Efficiency of Building Systems and Technologies

Considerable potential exists to reduce building energy usage and improve building energy efficiency. Currently, the major energy end uses in buildings are heating, ventilation, and air conditioning (HVAC); lighting, water heating, and refrigeration; and electronic devices, including computers. HVAC is the most energy intensive, and contributes to GHG emissions both through its consumption of fossil-fuel energy and through the refrigerants used as working fluids. HVAC energy usage can be reduced by decreasing the load or improving the efficiency of HVAC systems. With respect

RDD&D Opportunities for Advancing Clean and Cost-Competitive Electric Power Technologies

Clean and cost-competitive electric power technologies require both systems-level and technology-level RDD&D. Key systems-level RDD&D opportunities include the following:

- **Materials:** Develop advanced materials with properties that can meet the requirements of extreme conditions, processing techniques to produce them, and qualify them for use
- **Computing:** Develop high-performance computing, advanced algorithms, and control and decision science to improve power generation technologies and operations
- **Data management:** Improve technologies and software for data collection, analysis, and use (while protecting privacy) to strengthen planning and improve power operations
- **Multivariable portfolio analysis for power generation:** Develop well-defined and quantified metrics, modeling, and analytical tools to support an integrated approach to energy diversity
- **Energy-water nexus:** Evaluate system balances, tradeoffs, and sensitivities, and develop analytical tools to assess and optimize energy-water systems
- **Energy storage:** Develop analytical tools to evaluate energy storage options at multiple scales and technologies to integrate them in new power system configurations

RDD&D opportunities in clean electric power technologies include the following:

- **Carbon capture and storage (CCS):** Demonstrate second generation pilots, demonstrate retrofit of existing plants with CCS, demonstrate CCS technologies on industrial and natural gas sources, and develop a database characterizing storage options
- **Nuclear power:** Advance light water reactors, small modular reactors, high-temperature reactors, fast-reactors, fuel cycle technology, and hybrid systems.
- **Hydropower:** Advance materials and turbine designs, with an emphasis on modular systems and systems with reduced footprints
- **Wind power:** Develop integrated multiscale models of atmospheric flow through turbines, models and technologies for grid integration, offshore wind turbine technologies, and scaled up on-shore systems for both low and high wind speed regimes
- **Biopower:** Advance biopower technologies, including biomass gasification and biomass systems coupled with CCS
- **Solar (photovoltaic and concentrating solar power):** Reduce solar PV and CSP manufacturing and capital costs, reduce PV soft costs, improve grid integration—including with storage solutions, and identify and develop new PV materials and devices, particularly with abundant and environmentally-benign materials
- **Geothermal energy:** Improve the characterization of geothermal resources, technologies for controlling fracture networks and improving subsurface access, and advance hybrid systems
- **Fuel cells:** Reduce component and system costs, address gas cleanup, and advance modeling and simulation
- **Marine hydrokinetic power:** Develop advanced controls, design compact generators, and address corrosion and biofouling

to lighting, more than 95% of the potential savings due to advanced solid-state lighting remains unrealized. Continued innovation is still needed. The convergence of information technology and energy systems, and the increasing needs for building systems and technologies to "transact" with the electric utility for demand reduction and other purposes are helping to spur innovations in building energy modeling, sensors, and controls. However, many building technologies are not being widely adopted in the marketplace, largely because of excessive first costs. RDD&D in the buildings sector has to emphasize both cost reductions as well as efficiency improvements. Miscellaneous electric loads, such as small appliances, chargers, and office equipment use an increasing fraction of the typical building's total energy load. As a result, the best approach will require achieving substantial energy reductions in a wide variety of devices such as with advanced power electronics. See textbox: *RDD&D Opportunities for Increasing the Efficiency of Building Systems and Improving Technologies*, which describes a number of areas where significant advances are possible, with substantial potential benefits.

RDD&D Opportunities for Increasing the Efficiency of Building Systems and Improving Technologies

Energy efficiency RDD&D opportunities in the buildings sector abound, from improvements in individual technologies to the full building system and its integration with other sectors. These include the following:

Building thermal comfort and appliances

- Develop materials that facilitate deep retrofits of existing buildings (e.g., thin insulating materials)
- Improve low-GWP (global warming potential) heat pump systems
- Improve tools for diagnosing heat flows over the lifetime of a building
- Develop clear metrics for the performance of building shells in heat management and air flows

Lighting

- Develop test procedures for reliably determining the lifetime of light-emitting diodes (LEDs) and organic light-emitting diodes (OLEDs) products
- Understand why LED efficiency decreases at high power densities
- Develop high-efficiency green LEDs
- Develop glazing with tunable optical properties (also needed for thermal load management)
- Develop efficient, durable, low-cost OLEDs

Electronics and miscellaneous building energy loads

- Design more efficient circuitry and more flexible power management
- Standardize communications protocols for managing building systems and integrating them with external systems
- Develop wide bandgap semiconductors for power supplies

Systems-level opportunities

- Develop energy harvesting systems to provide power for wireless sensors and controls
- Improve the design and cost effectiveness of accurate, reliable sensor and control systems
- Develop algorithms that allow building sensor and control systems to automatically optimize operations across desired factors
- Develop easy-to-use, fast, accurate software tools for design and operations, including open source software
- Improve support for co-simulation with other modeling engines
- Incorporate more decision science research in buildings energy issues such as design and operations while protecting privacy
- Develop components and system designs that allow building devices to share waste heat

11.5 Innovating Clean Energy Technologies in Advanced Manufacturing

The manufacturing sector consumes 24 quads of primary energy annually in the United States or about 79% of total industrial energy use. However, the energy impacts are much broader as manufactured goods affect the production, delivery, and use of energy throughout the economy. Improved efficiencies in manufacturing technologies can drive economy-wide energy impacts at three levels:

- Manufacturing unit operation systems
- Production/facility systems
- Supply-chain systems

There are significant RDD&D opportunities at each of these levels, as described in the textbox: *RDD&D Opportunities for Clean Energy Technologies in Advanced Manufacturing.*

RDD&D Opportunities for Clean Energy Technologies in Advanced Manufacturing

The systems framework, at the unit operations, facility, and supply-chain levels, outlines ways to improve the energy and emissions footprint of the manufacturing sector. RDD&D opportunities for consideration include the following:

- **Process heating systems:** These systems account for nearly two-thirds of onsite manufacturing energy use; opportunities to reduce energy consumption include lower-energy processing (e.g., microwave heating), integrated systems, and advanced controls.
- **Motor-driven systems:** Motor-driven systems account for more than two-thirds of manufacturing electricity use; key opportunities to reduce energy consumption include

optimized motor system design, greater use of variable frequency drives, wide bandgap semiconductors, and leveraging the latest information technology advances for more intelligent power use.

- **Process intensification:** The integration of multiple unit operations into a single piece of equipment can reduce energy use, waste generation, and environmental impacts.
- **Roll-to-roll processing:** This fabrication technique enables low-cost production of complex-functional, large surface area devices needed for many clean energy applications such as flexible electronics for solar panels and membranes for low-energy separations.
- **Additive manufacturing:** In comparison with conventional subtractive manufacturing techniques, additive (3D printing) techniques can reduce materials waste, eliminate production steps, and enable new products that cannot be fabricated via conventional methods.
- **Combined heat and power:** The concurrent production of electricity and useful thermal energy from a single energy source can reduce fuel requirements compared to generating power and heat separately. Additionally, combined heat and power generation is typically performed onsite, increasing resiliency.
- **Waste heat recovery:** Generated waste heat can be captured and re-used by redirecting waste streams for use in other thermal processes, or by converting the waste heat to electricity.
- **Advanced sensors, controls, platforms, and modeling for manufacturing:** Automation, modeling, and sensing technologies enable real-time and proactive management of energy, productivity, and costs.
- **Industrial demand-side management:** By shifting electricity use away from peak times, demand on the grid can be better managed to match supply, allowing industrial consumers to avoid high rates.
- **Advanced materials manufacturing:** Computational modeling and data exchange could greatly accelerate the process of new materials discovery by minimizing trial and error.
- **Critical materials:** Many clean energy technologies are heavily reliant on critical materials (e.g., neodymium in a wind turbine permanent magnet). More secure and sustainable supply chains will more effectively advance technologies reliant on critical materials.
- **Sustainable manufacturing:** Material flow analyses reveal energy savings opportunities from products designed for re-use, technologies that enable greater use of secondary materials, and technologies that reduce raw materials requirements.
- **Direct thermal energy conversion materials, devices, and systems:** Technologies that convert energy from one form to another without intermediate steps (e.g., thermoelectrics for heat-to-electricity) can be used for waste heat recovery, efficient heating and cooling, and other applications.
- **Materials for harsh service conditions:** Opportunities include higher-temperature, higher-efficiency power plants; corrosion-resistant pipelines; and safer nuclear fuel claddings.
- **Wide bandgap semiconductors:** Wide bandgap semiconductors can enable smaller, lighter, and higher-efficiency power electronics compared to conventional silicon-based devices.
- **Composite materials:** Lightweight, high-strength, and high-stiffness structural composite materials could provide energy and environmental benefits in lightweighting applications such as vehicles, wind turbines, and gas storage.

11.6 Advancing Systems and Technologies to Produce Cleaner Fuels

Fuels directly supply 99% of the energy needed by our national transportation system and 66% of the energy needed to generate our electricity. In particular, fossil fuels account for 82% of total energy use in the United States. After several decades of generally flat (natural gas) or declining (oil) production, production of shale gas and oil has sharply increased in the United States in the past half-dozen years. Commercial production of cellulosic biomass fuels is poised to begin in 2015 after many years of research and development. Public-private partnerships are beginning to supply hydrogen to refuel the first commercially available consumer fuel cell electric vehicle.

The tradeoffs between conventional and alternative fuels—including cost, performance, infrastructure, security, and environmental impacts—occur across different time frames. An understanding of the diverse technological options in the fuels sector can support an informed RDD&D strategy going forward (see textbox: *RDD&D Opportunities for Advancing Systems and Technologies to Produce Cleaner Fuels).*

RDD&D Opportunities for Advancing Systems and Technologies to Produce Cleaner Fuels

The fuels sector—oil and gas, biofuels, hydrogen, and others—has very different levels of maturity and corresponding differences in the types of RDD&D needed and the appropriate public and private roles for each. RDD&D opportunities for consideration include the following:

Oil and gas

The economics of oil and gas are well understood. The shale revolution has increased confidence in sustained low natural gas prices, and the increase in domestic petroleum production has softened the impact of a volatile global oil market. The carbon footprint of these fuels, though, is large, and additional environmental concerns must be addressed. Specific technology opportunities include the following:

- Minimize the safety and environmental impacts of unconventional oil and gas development
- Protect groundwater, reduce water use, and protect air quality
- Reduce methane leaks associated with pipelines and compressors
- Develop understanding of induced seismicity
- Develop understanding required for commercial production of natural gas from natural hydrate deposits

Bioenergy for fuels

Advanced biofuels have the potential to significantly reduce GHG emissions compared to fossil-derived transportation fuels. There are many options in both feedstock and conversion technologies adaptable to regional resources and market demands. They could potentially supply about 25% of current U.S. transportation fuel demand. Biofuels should be used in sectors most difficult to electrify (such as aviation, trucking, marine, and other similar applications). However, cost of production is currently high, and production capacity is insufficient to meet market demand. Key technology areas to be addressed include the following:

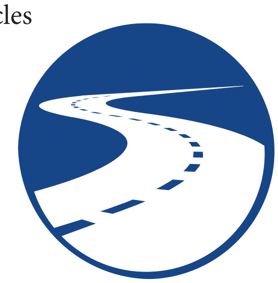
- Reduce costs of feedstock production, logistics, and conversion
- Produce and manage a consistent suite of lignocellulosic feedstocks
- Improve enzymes and micro-organisms for biochemical pathways and improving catalysts and processes for thermochemical pathways
- Develop high-value bio-products and bio-based inputs to chemicals

Hydrogen

Hydrogen is a zero-carbon energy carrier that could be produced entirely from domestic energy resources. Some technologies for producing, distributing, and using hydrogen are mature, but the costs of converting the end-to-end fuels infrastructure to accommodate hydrogen are high. Furthermore, hydrogen production from low- or zero-carbon resources is currently not economically competitive. Specific technology areas to be addressed include the following:

- R&D of materials and systems innovations to improve efficiencies, performance, durability, and reduce cost
- Address safety across all hydrogen production, delivery, storage, and dispensing options

11.7 Advancing Clean Transportation and Vehicle Systems and Technologies



Transportation provides personal mobility, freight delivery, and other mobile services to individuals and to the economy. It is the primary user of petroleum in the United States and a major emitter of GHGs and EPA-regulated criteria pollutants. Currently, light-, medium-, and heavy-duty vehicles account for approximately three quarters of transportation energy use and emissions. To greatly reduce GHG emissions, a larger share of vehicles must more efficiently use fuels and/or use lower-carbon energy, as it is not currently possible to capture and store carbon dioxide emissions from small, mobile sources. The technology portfolio uses complementary approaches that together shape an integrated research and development strategy for GHG emissions reduction, including component efficiency improvements, electric drivetrains, renewable fuels, and transportation system efficiencies. Efficiency opportunities exist in all modes, and in many cases represent the most cost-effective mechanism to reduce petroleum use and emissions in the near term. For light-duty vehicles, drivetrain electrification is a promising pathway to eliminate mobile source emissions and increase diversity of energy resources. Two of the most promising electrification options are hydrogen fuel cell vehicles and battery electric vehicles, but both still face substantial cost and performance challenges (see textbox: *RDD&D Opportunities in Clean Transportation and Vehicle Systems and Technologies*).

RDD&D Opportunities in Clean Transportation and Vehicle Systems and Technologies

RDD&D opportunities to improve vehicle efficiency and use clean fuels are described below for conventional and new electric and fuel cell vehicles, from individual components to the systems level. Key opportunities for consideration include the following:

- **Fuel economy** improvement with advanced combustion engines and more energy efficient vehicle systems.
- **Fuel-vehicle co-optimization**, to better use novel low-carbon fuels, achieved through integrated R&D across the fuel-vehicle system.
- **Lightweighting** of vehicles can improve efficiency across all drivetrains and vehicle classes.
- **Electric drivetrain** vehicles are a key strategy to reduce petroleum use and emissions from light duty vehicles. Plug-in electric vehicles, fuel cell electric vehicles, or a mix can offer this benefit.
- **Battery cost, weight, and reliability** improvements, together with power electronics, controls, and system research, can reduce the cost and improve performance of all electrified vehicles.
- **Power electronics, traction motor(s), and controls** research must reduce costs for technologies to be competitive.
- **Fuel cell vehicle** penetration in the light-duty market requires R&D to increase the durability and lower the cost of fuel cells, and lower the cost, volume, and weight of on-board hydrogen storage.
- **Fuel cell systems** should operate at 65% efficiency with an ultimate goal of 70% and be durable for 5,000 hours (equivalent to a vehicle life of about 150,000 miles). The following performance-related barriers need to be addressed: 1) sub-optimal utilization of platinum group metal content in current catalysts, 2) low performance of current catalysts and electrodes, 3) low performance of membranes under the hot and dry conditions, and 4) lack of understanding of the role of electrode composition and microstructure on fuel cell performance and durability.
- **On-board hydrogen storage** should provide a driving range of more than 300 miles at a competitive cost without compromising safety, performance, or interior space.
- **Other transportation modes**—including aviation, marine, rail, and off-road equipment—have significant efficiency improvement potential. These modes are currently a smaller but growing share of total petroleum use and emissions and increasing their efficiency is an area for future research.
- **A systems perspective** on transportation and technologies will enable future investment in smarter transportation systems and technologies. For example, vehicle connectivity and automation is an emerging issue in transportation energy, but initial research is needed to evaluate possible investment pathways.

11.8 Crosscutting Opportunities

Many technology themes transcend specific energy sectors. The analyses conducted for this QTR identified twelve technology RDD&D areas that cut across the six sectors. These avenues of research, with co-benefits across multiple sectors, should be pursued in an integrated manner through new research initiatives and/or by facilitating more communication between, and enhanced alignment of, existing activities. Advances in one area can lead to benefits in others.

The identified crosscutting opportunities fall into two categories: 1) technical topics, and 2) enabling tools. Technical topics include the following:

- **Grid modernization:** The electric grid is transitioning from a centrally-controlled, predictable system with one-way power flows in distribution to a much more distributed, stochastic, and dynamic system with bi-directional flows in distribution. Growth in the deployment of variable generation, electronic converters, and digital communications and control technologies is impacting core characteristics of the electricity system. Grid-related technologies need to evolve with the changing supply and end-use technologies landscape. Simultaneously, the RDD&D associated with technologies that connect to the grid (e..g, renewable power supplies, efficient motor controllers, and smart loads) should consider the evolving interface with the grid. If electricity displaces petroleum and natural gas in electric vehicles and heating applications, respectively, the grid may serve an even more central role in the future energy system. The RDD&D opportunities identified for this rapidly evolving sector include planning models. operational tools, transmission components, distribution hardware, control systems, electricity storage and cybersecurity. These opportunities need to be developed in anticipation of an agile, flexible, and resilient electric power system to enable effective integration of variable supplies and participatory demand.
- **Systems integration:** Energy systems are increasingly interconnected to one another and to other systems such as water and materials supply. Potential benefits of integrated systems include efficiency, resource savings, reduced GHG emissions, and increased resiliency. There are also challenges and risks associated with systems integration such as potential bottlenecks and points of failure. Appropriate application of systems integration requires understanding, control, and optimization across multiple sectors, time frames (e.g., fractions of a second for operations to years for planning), spatial scales (devices, buildings, campuses, city, region/state, nation), and functions (e.g., data, analysis, controls, and markets). Integration also requires an understanding of costs, particularly the capital costs of deploying new and/or integrative technologies, as well as the financial implications of deployment and operations. Integration of technologies such as fuel cells, energy storage, rooftop solar, and microgrids will all be affected by systems integration strategies. RDD&D in this area could enable system designers and operators to work toward an optimal level of interconnectedness with risk mitigation through appropriate system sizing and graceful disconnection strategies.
- **Cybersecurity:** The extensive digital technologies that enable significant improvements to new energy systems also increase the attack surface for cyber intrusion. Opportunities to improve cybersecurity are being actively pursued for the energy sector, including electricity generation and oil and gas production, the supervisory control and data acquisition systems for automated controls of building energy use, the information technology-enabled manufacturing space, and connected and automated vehicles. Rigorously applied cybersecurity best practices, tools that measure the security and resilience of energy systems, and networks and systems that adapt to and self-configure in the presence of evolving cyber threats, can help ensure the cyber integrity of components through the entire energy system supply chain.

- **Energy-water:** Water use is intertwined with oil and gas production, growing and processing biomass, cooling thermal power plants, numerous manufacturing processes, and direct use by humans. Conversely, substantial energy is used to withdraw, transport, clean, and condition water and ultimately return it to the environment. Effective RDD&D can improve the efficiency of these processes, or alternately, find cost-effective low/no water alternatives. Opportunities include novel nano-structured membranes, and new chemical and biological-based treatment technologies. There is also broad opportunity to accelerate the development of databases, modeling, and analysis to better understand and address water quality, availability, and fate. Furthermore, water resources are expected to change in location and timing due to climate change impacts; fundamental advances in climate science and integrated assessment could help to better understand these unknowns. The long lifetimes and high costs of installed energy equipment and water infrastructure underpin targeted and effective energy-water R&D in the context of climate change.
- **Subsurface:** Oil and gas production, geothermal energy, carbon capture and storage (CCS), and nuclear waste disposal all rely on effective control and management of the subsurface environment. Foundational scientific research and crosscutting applied technology development can improve characterization and manipulation of subsurface formations for all of these applications. Quantitative prediction and control of subsurface fractures, fluid flow, complex physicochemistry, and rock response to this control under widely variable spatial and temporal scales—nanometer to kilometer and microseconds to millennia—is key to these sectors. Since the majority of the subsurface cannot be observed directly, significant advances in sensing technologies, modeling, and simulation are required to advance the state of the art. This needs to be done at low risk in a challenging high-pressure, high-temperature, corrosive environment with effective ongoing monitoring of reservoir integrity.
- **Materials:** Materials properties dictate the performance limits of an energy technology. Changing these properties in the next generation of materials can dramatically improve performance; for example, increasing the strength-to-weight ratio of materials used in vehicles can improve fuel efficiency. Building solar cells with earth-abundant materials having high photon-to-current efficiencies can help make solar energy cost competitive. Materials that are stable at extreme temperatures or large radiation flux can improve the efficiency of fossil and nuclear electric power plants, respectively. New materials for next-generation energy technologies are inherently more complex, containing both more components and novel nanoscale structures. Materials R&D requires leveraging experimental and computational tools. Designing materials to meet specific performance needs requires research that couples theory, modeling, and simulation with *in situ* and *in operando* characterization. Materials designed *in silico* with novel structures will require novel nanoscale synthesis techniques and subsequent characterization under operating conditions to validate computational models. Integrating new materials into energy technologies requires advanced capabilities for manufacturing scale-up, real-time process characterization, process control, and performance validation. The importance of these capabilities is reflected in the multiagency Materials Genome Initiative launched in 2012. Taken together, these capabilities have the potential to dramatically accelerate and reduce the cost of developing new energy technologies.
- **Fuel-engine co-optimization:** Engine performance, which drives efficiency across the entire transportation fleet, can be limited by the properties of the fuels available. With bio-derived, and/or other synthetic fuels, there is an opportunity to optimize the end-to-end fuel-vehicle system for improved efficiency and reduced environmental impacts. Engines that take advantage of the special properties of appropriately engineered fuels may be able to operate at higher compression ratios and under alternate combustion regimes (such as homogeneous or partly stratified charge). Similarly, fuels

derived from non-petroleum feedstocks can be formulated for use in advanced technology engines. A co-optimized fuel and engine system therefore has the potential to improve fleet-scale efficiency and reduce vehicle-out GHG emissions. Fuels derived from low, zero, or negative-carbon feedstocks and processes will result in further emission reductions. Foundational science and technology research that crosscuts the fuels and transport sectors is required to achieve these goals.

- **Energy storage:** Effective and economic energy storage is essential to the transportation sector as well as the evolving electric grid. Storage technologies with higher gravimetric and volumetric energy density that currently available are required for electric vehicles if they are to compete with conventional vehicle range and refueling times. For the grid, lower-cost energy storage will likely be important for high penetrations of renewable resources such as distributed photovoltaic systems, in conjunction with fast-acting technologies required to provide voltage support, frequency regulation and other grid services. RDD&D on efficient, durable, and safe energy storage technologies could enable transformational change across transportation, electric power, and buildings.

The four crosscutting enabling tools listed below represent existing and evolving capabilities in the public and private sectors that, when directed at supporting energy technology and system RDD&D, could drive transformational innovations. Key RDD&D opportunities for consideration include the following:

- **Computational modeling and simulation:** Large increases in computational capability, driven both by advances in chip technology and integration of more processors into massively parallel supercomputers, have enabled simulation of more complex physical phenomena. This has impacted all stages of the RDD&D process. **Research** in areas including materials for extreme environments, biofuel production, and photovoltaics, is accelerated, thanks to larger and more complex molecular-level simulations. Engineers are increasingly relying on advanced simulation in the design and **development** processes for novel internal combustion engines, wind power systems, and fossil power plants, reducing the need for frequent and expensive prototyping. These same simulation capabilities are enabling modeling and simulation of the behavior of new energy projects at the **demonstration** stage. Advanced simulation capabilities are allowing **deployed** energy systems to run more efficiently. For example, modeling and simulation tools developed through collaborations with DOE's national laboratories and industry are used to understand how existing nuclear reactors can be operated more safely and efficiently, while grid simulation is improving decision making without hardware modifications. In all of these areas, increases in computing power; the development of new mathematical algorithms; and increased integration of simulation with large-scale experiments, technology design processes, and large-scale energy systems will increase the importance of advanced simulation in energy technology.
- **Data and analysis:** Opportunities to apply advanced analytics and management of extremely large data sets transect the entire clean energy economy. In particular, the ability to obtain actionable information from an ever-increasing quantity of data ("Big Data") is both an opportunity and a research need. Increasingly inexpensive and effective ways to monitor and control data-dense energy systems are enabling novel and potentially more resource-efficient, transaction-based control. Enhanced abilities to establish complex correlations in massive and disparate data sets and by automatically synthesizing the results of large quantities of research can materially advance the scientific process. The 2011 QTR established a need for strong capabilities in technology assessment, cost analysis, program planning and evaluation, and impact analysis; in QTR 2015, this continues as an important and central function.
- **Analysis of complex systems:** Given the convergence of the energy system and its technical systems, advancements in complex systems analysis need to be coupled with the benefits of the confluence of theory, modeling, synthesis, and characterization and advancements in areas of computational

modeling and simulation, data and analysis, and decision science (including risk analysis) to effectively facilitate the transition to a clean energy economy. The development of a predictive understanding of energy-relevant biological and environmental systems has applications from microbial biofuel production to carbon storage and environmental transport. The detailed understanding of how Earth's dynamic, physical, and biogeochemical systems interact enables prediction of climate change impacts and planning for future energy needs.

- **Characterization and control of matter at multiscales:** Extraordinary advances in observation and characterization of materials and chemistry have paved the way for manipulating materials at the nano- and mesoscale to create new tailored functionalities.
  - **X-ray light sources** provide ultra-high intensity focused X-ray beams that allow scientists to probe the structure of matter at the electronic, atomic, and molecular levels. The knowledge gained will enable scientists to design revolutionary new forms of matter with tailored properties having applications in chemical, material, life, and geosciences. X-ray free electron lasers, such as the Linac Coherent Light Source at SLAC National Accelerator Laboratory are providing entirely new scientific capabilities to probe the ultrafast time evolution of complex chemical reactions.
  - **Neutron sources** such as the Spallation Neutron Source at Oak Ridge National Laboratory are ideal for probing the structure and dynamics of materials containing light atoms, magnetic materials, or macroscale samples that require deep penetration. Emerging neutron source technologies can enable new science from condensed matter to biomaterials and world-leading resolution in 3D structural measurements.

The nanoscale science research centers integrate theory, synthesis, fabrication, and characterization of novel nano- and mesoscale systems to develop the next generation of materials for energy technology. New techniques in fabrication based on high-throughput synthesis and self-assembly and characterization by multifunctional probes with increasing spatial and temporal resolutions have the potential to accelerate the pace of materials discovery and development.

11.9 Analysis and Execution

Pursuing RDD&D opportunities that are impactful to the nation's security, economic, and environmental goals require analytical methodologies in portfolio management and innovative frameworks through which to pursue the scientific and technical challenges.

11.9.1 RDD&D Portfolio Analysis

Evaluating the potential impact of an RDD&D portfolio requires multiple considerations. For example, the potential performance improvements that change the security, economic, and environmental impacts of a set of technologies must be characterized. Additionally, the potential market deployment (and its reliance on economies of scale, learning, business model assumptions, and additional supporting infrastructure) must be estimated and the resulting effects considered. The analytical tools are described in the following broad categories:

- **Technology planning and projection:** Many organizations perform roadmapping with inputs that include expert elicitation and estimates of technology readiness levels. This QTR discusses activities required for integrating this roadmapping process.
- **Analysis tools and metrics:** There is no single metric that can be used to comprehensively assess and compare RDD&D opportunities. Rather, it is important to have a consistent and common set of tools

and metrics to enable effective comparison. Such tools include security assessments of reliability and resilience, financial analysis such as the delivered cost of energy services, and environmental metrics for GHG emissions and air, water, and land impacts. Life-cycle assessment methodologies can be used to frame these analyses.

- **Evaluation tools:** The risk of whether research will be successful, the uncertainties of a rapidly changing world, and the many interacting energy services needed together motivate the assembly of a portfolio of technologies for RDD&D. This can improve the likelihood of success, but because of the many ways different technologies may compete or complement one another, this also requires evaluating the entire portfolio and not simply individual technologies. Options space analysis, wedge analysis, integrated assessment models, and real-options valuation are some of the approaches to be considered for assessing the research portfolio.

The analytical tools developed in these areas should remain flexible to changes in investment decisions as conditions change.

11.9.2 RDD&D Execution

The paradigm of scientific inquiry pursued by a single investigator or small, co-located research team has expanded dramatically over the past decades to include both that original vision as well as a wide variety of multi-institutional, multi-investigator collaboration models. These models can accelerate the RDD&D process in three ways: 1) by enhancing "horizontal" information transfer between groups of researchers who work competitively and collaboratively on a topic, 2) by enhancing "vertical" information transfer between the different stages of the RDD&D pipeline, and 3) by transecting industry, national laboratories, and academia, each of which can bring complementary strengths to a given problem. Selection of the mechanism(s) to pursue any specific opportunity is a complex process. A selection of key existing and emerging mechanisms include the following:

- **Multidisciplinary, multiscale research:** Many federal agencies are moving toward vertically integrated, topically focused research activities. This fosters crossdisciplinary collaboration through an integrated research structure to tackle the most challenging science and engineering problems. The DOE-supported Centers, Hubs, and Institutes described in Chapter 9 are examples of such collaborations across disciplines and across basic science and applied technology development.
- **Technology transition to the economy:** The national laboratories can improve the nation's economy both by driving strategic industries in pursuit of national science driven missions in security, science, and energy; by generating and promulgating intellectual property; and by facilitating the access of private sector entities to the unique R&D capabilities and staffs of the laboratories. The R&D activities pursued by the national laboratories, and the knowledge gained in the process, thus can have both direct and secondary economic impacts.
- **Public-private consortia:** These activities are convened by government entities but include significant participation by industry. Consortia engage in precompetitive research activities under a formal agreement that covers the work to be performed and how information will be shared. Thus, consortia enable joint research on platform technologies and early stage research in a technical field and leave participants free to build on the shared information to create proprietary outcomes of commercial utility.
- **Alliances and coalitions:** Providing organizational and/or financial support to industrial alliances and coalitions—such as the Better Buildings Alliance and the Clean Cities Coalition—is intended to result in rapid propagation of best practices and broad uptake of technology innovations.

Continued innovation of novel modalities applied to different RDD&D opportunities is required by the nature of the challenges that these technologies address.

11.10 Concluding Thoughts

The systems perspective used in the development of this second Quadrennial Technology Review has enabled the identification of energy systems convergence, diversity within sectors, and efficiency everywhere as broad themes for organizing RDD&D activities. Additionally, the integration of fundamental research opportunities with technology development programs has enabled the identification of the confluence of advanced research tools, such as high-performance computing and materials characterization facilities, with design and control of complex systems, as a new paradigm in RDD&D.

Energy stakeholders can take advantage of the rapidly emerging set of tools for creating new generations of materials, devices, and systems for energy applications. Strengthened analysis and assessment programs should inform sector-specific and crosscutting RDD&D initiatives. Continuing to drive a well-diversified portfolio of energy research is essential to meeting the strategic objectives of the nation.