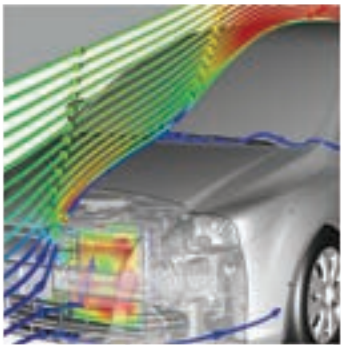
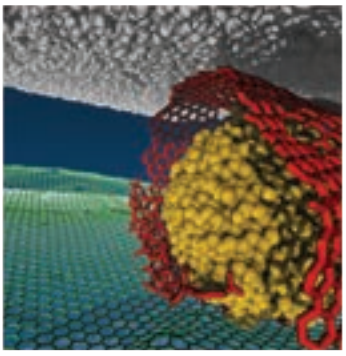




QTR





QUADRENNIAL TECHNOLOGY REVIEW

AN ASSESSMENT OF ENERGY TECHNOLOGIES AND RESEARCH OPPORTUNITIES

September 2015

About the Cover

Image 1: Image courtesy of Oak Ridge National Laboratory (ORNL). ORNL researchers study the potential of Eastern Cottonwood trees as an alternative biofuel feedstock.

Image 2: Photo of utility-scale wind turbines onshore and off the coast of Copenhagen, Denmark. The United States' vast wind resource both on land and offshore represent important options for America's clean energy future. Photo credit iStock 6877403.

Image 3: Image courtesy of ORNL and Ford Motor Company. Simulations on ORNL supercomputers helped Ford optimize the effectiveness and fuel efficiency of engine bay designs.

Image 4: Image courtesy of Sandia National Laboratories. Working with utilities, states, other government agencies, and technology developers, DOE is facilitating modernization innovations that fully address safety, security, and reliability requirements of the U.S. electricity system.

Image 5: Image courtesy of Lawrence Berkeley National Laboratory. Researchers at the window testing facility at Lawrence Berkeley National Laboratory are developing dynamic windows treated with nanocrystals that block heat from the sun when a small electrical current is applied—particularly useful for hot summer days.

Image 6: Image courtesy of Argonne National Laboratory. This large-scale simulation depicts a phenomenon called superlubricity, or a condition of extremely low friction. Argonne scientists used Mira, one of the fastest supercomputers, to identify and improve a new mechanism for eliminating friction, which fed into the development of a hybrid material that exhibited superlubricity at the macroscale for the first time.

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Message from the Secretary of Energy

The energy sector in the United States has been changing rapidly—dramatically increased oil and gas production and renewables deployment; decreased carbon dioxide emissions; enhanced energy-intensive manufacturing and introduction of technology enablers for next generation manufacturing; expansion of electric vehicles, smart grid, and distributed generation deployment; increased risk to energy infrastructure from extreme weather and sea level rise, regional water stresses, cybersecurity and other factors. Most of these developments have been materially advanced and risks attenuated by Department of Energy (DOE) research, development, demonstration, and deployment (RDD&D) programs over several decades. All are being addressed today in ways that will advance the goals of economic clean energy production, delivery and end use, with reliability and resilience.

This second Quadrennial Technology Review (QTR) explores the current state of technologies in key energy sectors and the R&D opportunities present in the mid-term. It is intended to frame a blueprint for DOE energy technology development and for the enabling science for future technology breakthroughs.

DOE has many tools to advance this agenda across the RDD&D innovation chain, among them: Energy Frontier Research Centers addressing energy-related scientific grand challenges; early stage technology development through ARPA-E and Innovation Hubs; applied energy programs (Energy Efficiency and Renewable Energy; Fossil Energy; Nuclear Energy; Office of Electricity Delivery and Energy Reliability) that span RDD&D; the Loan Program Office that supports initial commercial deployment of advanced clean energy technologies. The QTR informs all of these programs—and others—with technology assessments in electricity, buildings, advanced manufacturing, fuels, and transportation and vehicles, as well as addressing key enabling capabilities such as high-performance computing and fundamental understanding of materials. The QTR also aligns with the Department's increased focus on crosscutting R&D, such as grid modernization, subsurface science and engineering, and the energy-water nexus. A primary goal is continuing cost reduction of clean energy technology to spur the pace of deployment even more.

Progress will require continuing partnerships with innovators across the nation. The Department's network of seventeen national laboratories is obviously critical both for their work on energy science and technology and for providing unmatched research capabilities for the broader research community. Partnerships with university scientists and engineers, researchers at both established and entrepreneurial companies, federal and state agencies, and others are also essential.

Despite the energy transformation that we have seen and have been part of during the Obama Administration, we face many ongoing energy challenges—mitigating the risks of climate change through clean energy and greatly reduced greenhouse gas emissions, modernizing our energy infrastructure with resilience against the

full risk spectrum, enhancing energy security for the United States and our friends and allies. We are convinced that energy science and technology hold the key to meeting these challenges through technology, business model, and policy innovation. As such, the QTR, together with the ongoing Quadrennial Energy Review, will do much to inform DOE's efforts and contributions for years to come. We hope it will be similarly useful to the energy community at large.

Ernest J. Moniz
Secretary of Energy

Message from the Deputy Under Secretary for Science and Energy

QTR 2015 describes the current energy landscape, the potential for improvement in systems and technologies, and a wide-ranging set of related RDD&D opportunities. Energy technologies are assessed with respect to their potential security implications, economic and environmental impact, and engineering feasibility (costs, benefits, and theoretical limits), and technological maturity. This forward-looking assessment of energy science and technology topics will inform the RDD&D portfolio of the nation's energy enterprise.

The world of energy-related research is rich with opportunities to help create a secure, resilient, economically efficient, and environmentally responsible set of energy systems. Our analysis demonstrates that innovation at the systems level offers real potential for revolutionary changes to the ways we deliver and use energy. Those systems will rely on more efficient energy conversion technologies, and on plentiful, domestic and earth-abundant resources and an enhanced ability to design and operate them as they grow in scale and complexity. The QTR examines a diversified portfolio of energy research that will enable continued leadership by the United States in our quest to provide the clean energy services essential to modern societies.

Each of the six sectors of our energy system described in this report (grid, power, buildings, manufacturing, fuels and transportation) includes ample opportunity to advance technology at the component, device, and system levels. Just as importantly, the QTR identifies crosscutting technologies and disciplines that impact multiple sectors. These include a confluence of computational and empirical capabilities that is ushering in a new era of "systems by design" in materials, chemistry, biology, and engineered systems throughout the economy. Nowhere is this more true than in the domain of energy, where our expanding knowledge of the physical world is intrinsically linked to the development of technologies and systems at multiple scales.

QTR 2015 represents a monumental effort to combine information from across a wide spectrum of systems and technologies into a single volume. And that effort has resulted in an important set of insights. The analysis contained in these pages supports the technology component of a much broader national strategy to evolve our energy system, improving its security, resilience, economic impacts, and environmental responsibility along the way.

The analysis compiled hundreds of recent studies and reports that describe energy science, technology, and systems. Stakeholders across the energy enterprise are represented. The results of hundreds of workshops, most held in the few years prior to this document's publication, and many of which were highly focused on a specific technology, are incorporated. Additionally, nearly 200 representatives of energy industries, universities, and national labs participated in workshops held specifically to gather input for the QTR and to review its contents. Furthermore, nearly 500 energy experts provided written reviews of the QTR and its supporting technology assessments.

This QTR is intended to inform and inspire the community of stakeholders in the nation's energy system with a broad awareness of the full set of opportunities and a unity of thinking regarding strategies for advancement. For industry, the sum of the RDD&D pathways discussed herein will become opportunities to act in support of the nation's strategic energy objectives. For students, this review is an encyclopedia of potential career paths. And for energy experts in all professions, this is a reference document which supports a wide variety of activities and publications in pursuit of a secure, competitive, and clean energy system.

It is incumbent upon all of us who work on energy matters to take full advantage of this analysis of RDD&D opportunities as we work toward the energy systems of the decades to come. The scale of our energy challenges should not be underestimated, but this report gives us confidence that we can meet those challenges based on a fully enriched, diversified portfolio of RDD&D supported by government, industry, national laboratories, and universities.

Michael Knotek
Deputy Under Secretary for Science and Energy

Acknowledgment from the Under Secretary for Science and Energy

Secretary Moniz challenged us to do a comprehensive update to the 2011 QTR. The resulting QTR 2015 is the product of a dedicated and very hard-working team of individuals drawn from across DOE and the national labs, with additional input and review by hundreds of stakeholders across the energy landscape. This assessment is unrivaled in depth and breadth of its analysis of the energy technologies of today and the possibilities for those of the future.

The team that created QTR 2015 was assembled and ably led by Michael Knotek, Deputy Under Secretary for Science and Energy. His vision of what the report could be was the basis for what is here. Sam Baldwin used his encyclopedic knowledge of energy to lead the detailed effort. He worked tirelessly to shepherd a far-flung flock of contributors, to organize and write about myriad energy topics, and to weave them together into this overview report, accompanied by fifty in-depth technology assessments that describe the full effort. The process of assembling and reviewing the report was guided by an Executive Steering Committee that included Steve Binkley, Steve Chalk, David Conrad, Patricia Dehmer*, Julio Friedmann*, Doug Hollett*, Christopher (Chris) Johns, John E. Kelly*, Henry (Hank) Kenchington*, Harriet Kung, Robert (Bob) Marlay, David Mohler, Darren Mollot, David S. Ortiz*, Kimberly Rasar, Pilar Thomas*, Ellen Williams*, and Jetta Wong. Drafting of the individual chapters was done by the following individuals: Sam Baldwin, Gilbert Bindewald, Austin Brown, Charles Chen, Kerry Cheung, Corrie Clark, Joe Cresko, Matt Crozat, Jarad Daniels, Jae Edmonds, Paul Friley, Jeff Greenblatt, Zia Haq, Kristen Honey, Marcos Huerta, Ziga Ivanic, William Joost, Akhlesh Kaushiva, Henry Kelly, Dan King, Adam Kinney, Michael Kuperberg, Alex Larzelere, Heather Liddell, Steve Lindenberg, Michael Martin, Colin McMillan, Elena Melchert, Josh Mengers, Eric Miller, James Miller, George Muntean, Pat Phelan, Charles Russomanno, Ridah Sabouni, Ann Satsangi, Andrew Schwartz, Dev Shenoy, A.J. Simon, Gurpreet Singh, Emmanuel Taylor, Jake Ward, and Bradley Williams, with review and evaluation by chapter by the ESC members identified above with "*" and others who served as co-champions, Mark A. Johnson, Roland Risser, and Reuben Sarkar.

The analyses of energy topics and the assembly of the report drew heavily on the expertise of the seventeen DOE national labs, with particularly important contributions from Argonne National Laboratory, Brookhaven National Laboratory, Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Pacific Northwest National Laboratory. We also thank our many colleagues across DOE and the lab complex, from other agencies, and from universities and industry, who contributed a vigorous peer review.

We thank Oak Ridge Institute for Science and Education (ORISE) for their exceptional effort in producing the final version of the report. Thanks also go to the editorial review team led by Margaret Schaus with contributions from John Cabaniss, Patty Walters, Melissa Ardis, BCS Incorporated, and New West

Technologies. And we thank Laurie Hakes, Noor Khalidi, and Latreese Lambirth for providing general support throughout the QTR 2015 effort.

It was my good fortune to join this team as the report was nearing completion. It is my pleasure now to recognize with gratitude all those whose hard work and thoughtful analysis is assembled here.

Franklin Orr
Under Secretary for Science and Energy