

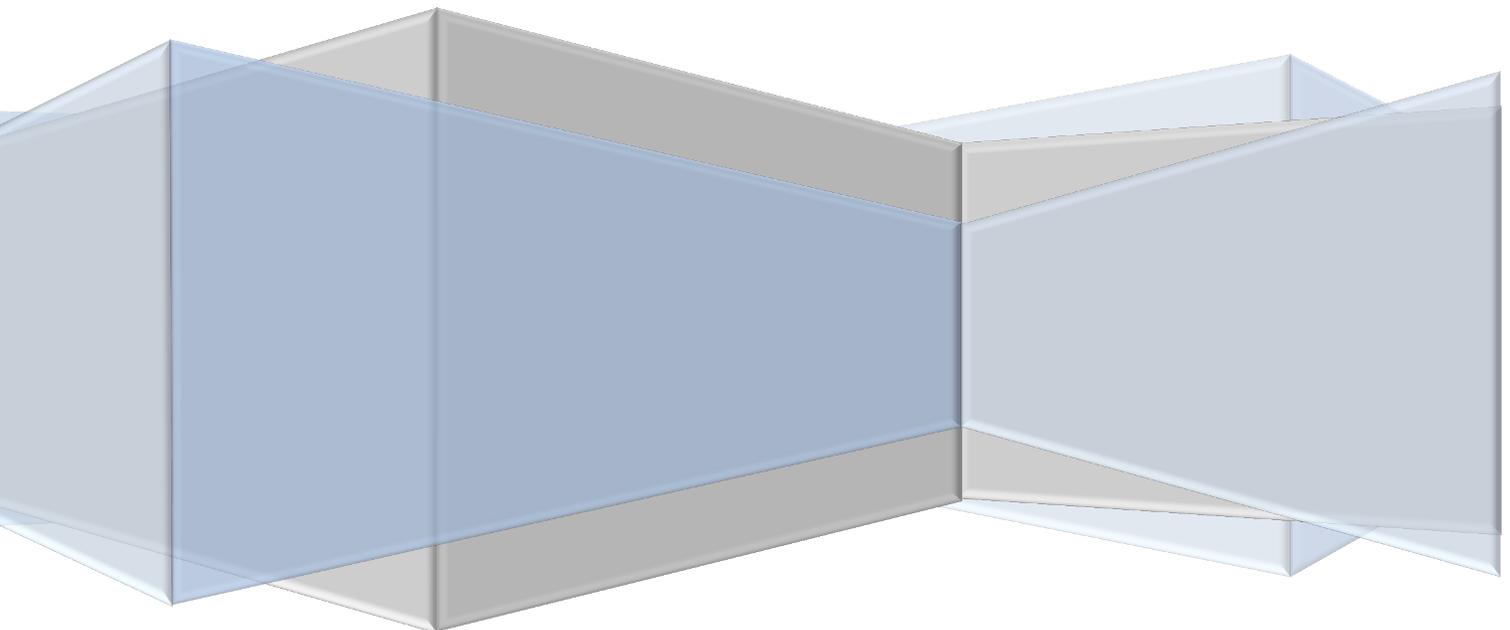
Energy Systems Integration

A Convergence of Ideas

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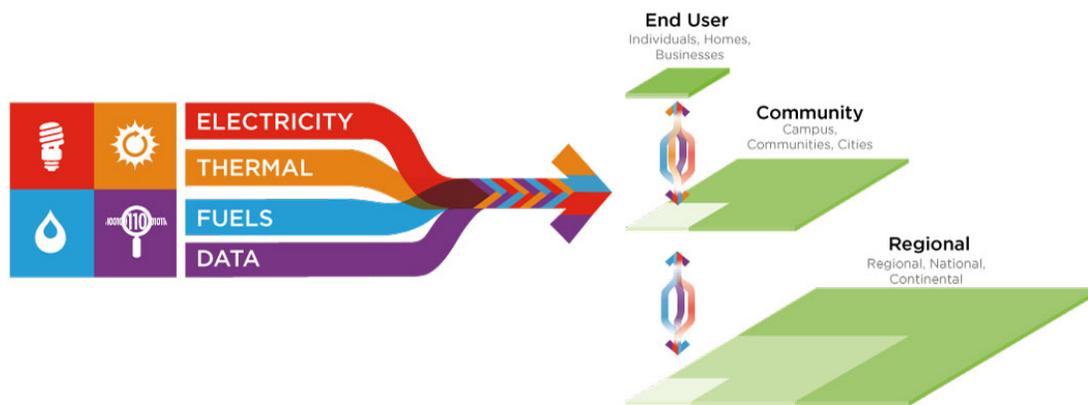
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Background

Our energy system includes not only renewable, nuclear, and fossil energy sources but also electrical, thermal, and fuel energy pathways that convert and deliver energy services at different physical scales. Interactions and interdependencies are increasing among the pathways and across the physical scales of the energy system as well as between the energy system and other systems such as data and information networks. Energy systems integration (ESI) enables the effective analysis, design, and control of these interactions and interdependencies along technical, economic, regulatory, and social dimensions. By focusing on the optimization of energy systems across multiple pathways and scales, we can better understand and make use of potential co-benefits that increase reliability and performance, reduce cost, and minimize environmental impacts.



Energy systems integration

Energy systems have evolved from small, local, single-service systems (e.g., the steam engines that powered the Industrial Revolution) into highly integrated, continental systems that deliver energy services (e.g., natural gas and electrical transmission/ distribution systems that deliver energy to our homes and businesses). Integration is also increasing between the energy system and other systems—such as data and information networks and water systems—that traditionally have not been linked with energy.

The pace of integration in our energy system is being driven by many diverse but interrelated factors.

Traditional economic factors, such as growing economies of scale and energy waste reduction, are driving ESI, while global trade and market mechanisms are causing a convergence with new security threats and environmental concerns. Political and energy convergence is also causing increased integration. For example, large-scale transmission projects in China will bring wind energy from interior sources to coastal loads, and plans are under way to link wind energy among countries around the North Sea. Because of the dispersed nature of renewable resources and the benefits of harvesting renewable energy from high-resource areas, better coordination and control across large geographic areas is needed.

Political and Energy Convergence

In the European Union, 27 countries have a goal to collectively reduce carbon dioxide emissions, which is driving a continental approach to energy security and sustainability. A particularly notable instance of this is intergovernmental plans to develop the off-shore wind resources of the North Sea.

The combination of low-cost monitoring and control and the integration of data and information networks with the energy system is enabling advanced control and coordination across the energy pathways and scales. For example, General Electric monitors a significant number of its wind turbines worldwide from two locations (Schenectady, New York, and Salzbergen, Germany) to provide maintenance and operational support. In addition, improved monitoring and control, reductions in local power production costs (e.g., from cost-competitive photovoltaics), interactive local energy management systems, and the potential electrification of automobiles allow consumers to play an increasingly influential role in the future of energy systems by giving them the opportunity to act as producers as well as consumers of energy and provide services to the larger energy system.

Urbanization, modernization, and economics are placing ever-increasing demands on systems around the world to squeeze more out of less. Building large-scale infrastructure (e.g., high-voltage transmission) is increasingly difficult in many parts of the world, and technology improvements are simultaneously driving growth in local generation. There is a need to optimally integrate and control these resources across multiple scales—from the local level to the global energy system.

These many factors driving the transformation of a cleaner, more intelligent, and integrated energy infrastructure are resulting in an increasingly complex energy system that, amidst all the change, is required to at least maintain current levels of efficiency, resiliency, and sustainability. As the complexity of the energy system increases, the challenges of maintaining stable, reliable, and economic operation become more difficult.

NREL and its partners recognize the growing importance of ESI as a critical multidisciplinary, multifaceted research and development area that will underpin the energy system of the future. We are developing a core competency to drive the development of the next generation of systems integration, simulation, operation, and controls and inform future energy system architectures, policies, and investments. We are assembling critical analytical and physical capabilities to address ESI with investments in NREL's Energy Systems Integration Facility (ESIF) and national and international work to highlight challenges and opportunities. This white paper is a small but significant part of that process.

Challenges

The ongoing transformation of the global energy system poses fundamental challenges to the creation of robust energy systems. Meeting the growing demand for energy is one of the most complex and challenging issues of our time.

We need to consider how the energy system can be robust with regard to many potential futures. There is uncertainty about how new technologies will integrate with the social and economic fabric of society. Fuel cost uncertainty can have significant impacts in the transportation and power generation sectors. Extreme events and unforeseen changes, such as the rapid development of U.S. shale gas, can be disruptive and have dramatic impacts. These

Energy Systems Integration Facility

NREL's Energy Systems Integration Facility addresses the challenges of large-scale integration of energy technologies into our energy systems infrastructure for all energy pathways—electrical, thermal, and fuel systems—by linking hardware experimentation and large-scale simulation environments.



examples illustrate the need to develop ESI as a research area with the key goal of proposing solutions that ensure a robust energy system that can adapt to a range of unknowns.

Energy systems are typically capital-intensive and designed to last decades. Many existing systems suffer from aging infrastructure and neglected upgrades. The International Energy Agency's *World Energy Outlook 2011* predicts that \$35 trillion will be invested in energy infrastructure over the next 25 years. This underlines the significant dangers of under- or over-investing based on weak assumptions and increased uncertainty.

ESI is fundamentally complex to a degree that is difficult to appreciate. Core technical complexity across a range of scales and physical domains is intertwined with social, political, and economic factors. Without a holistic approach, there is significant danger that local optimizations may produce a solution that is far from a global or societal optimum. Conversely, global optimization may lead to a "brittle" solution that risks reliability or security. A set of optimal subsystems may improve global results and resiliency, but the boundaries between subsystems are unclear, and interactions between subsystems have not been defined. Further, a sense of urgency must be maintained as changes are under way, and piecemeal changes may be difficult to reverse once established.

Opportunities

The drivers and challenges noted in this paper present significant opportunities to create new, robust energy systems that reduce cost and environmental impacts while increasing efficiency and reliability. Opportunities exist to capture co-benefits and improve the overall efficiency of our energy system. For example, in the United States alone, more than one-half of the energy generated is wasted by inefficient systems. Through a more holistic approach, there is an opportunity to increase efficiency using technologies such as combined heat and power and waste heat utilization.

Properly designed, efficiency improvements can also improve reliability, security, and flexibility. For example, using data and information technology, energy management systems can monitor building functions and adjust heating and ventilation systems to increase efficiency at a local level. If these new systems are well

Electricity and Thermal Systems Convergence

Denmark is integrating combined heat and power systems to increase energy efficiency and provide a more robust energy system. Denmark's 5.4 GW of combined heat and power provide 49% of its electricity and 80% of its district heating. The combined heat and power systems are part of the larger integration of wind and flexible load.

integrated into the larger energy system with correct control signals, the same local controls can be used to provide ancillary services to the grid to facilitate the use of more wind and solar energy.

The control and coordination goals of ESI require accessing and processing data and deriving knowledge to drive operations and performance of the energy system.

Increased deployment of energy system sensors and the associated derived knowledge can be used to optimize the design and operation of energy systems. For example, smart meters can provide detailed gas and electricity usage data that are invaluable to designers of future energy systems. Information and communication technologies can support entirely new market mechanisms, at a granularity and complexity beyond anything currently implemented, with the potential to unlock a

significant wave of innovation. Close coupling of energy equipment manufacturers and the information technology industry may yield new technologies and operation methods that can improve the operations of the energy system. Linking energy use to consumer behavior can also dictate how energy systems are designed and built. Energy information may well prove as critical to overall system efficiency as any production or end-use technology.

Within ESI, the opportunities for customers to benefit from improved efficiency, lower costs, and reduced environmental impacts are evident. Manufacturers and system operators will benefit from the ability to maximize the functionality of their systems with greater certainty and confidence before additional investments are made. And innovators will find a rich environment in which to develop new products and services.

Conclusion

The energy system is evolving, and it is in our collective best interest to guide it to a solution that delivers on all our goals and supports a range of possible futures. NREL's vision is to develop a robust and sustainable integrated energy system across energy pathways and physical scales.

Electricity, Data, and Information Networks Convergence

The electricity grid is being overlaid with an infrastructure that allows for more data, information, and control than ever before. The potential to implement more control of the grid is now a reality. While these technology changes are well intentioned, how the energy system will use the large data sets and how customers will respond to market signals is still unclear.

To realize the potential of ESI, NREL is building collaborative partnerships to bring in top researchers from technical, economic, and social disciplines to solve critical integration problems. Advancing the science of ESI will require new approaches to scalable modeling and simulation that incorporate the full suite of energy technologies, the ability to collect and create knowledge from large sets of energy data, paradigms that fully utilize the vast number of controllable devices, and new tools and guidance to shape future scenarios. Our approach builds on research in new control architectures that are optimized at smaller scales but can be aggregated to optimize energy systems at any scale and would allow replicable energy solutions across boundaries of existing and new energy pathways.

The energy system is complex and highly coupled, so linking simulation to experimentation provides significant insights that cannot be achieved by either separately. This requires tapping newly developed integration facilities, such as NREL's ESIF, that combine hardware testing at proper scale with simulation environments that can link the energy pathways. Through ESIF, NREL is developing a competency to allow the empirically driven refinements of systems integration simulations, operations, and controls to inform future energy system architecture, policy, and investments. These tools, along with a commitment to understanding integration at scale, will allow us to shape the energy system of the future.

The convergence of energy disciplines, environmental factors, and economic challenges is demanding a new focus on world energy goals and how we will meet them. Numerous examples (e.g., wind power in Ireland, combined heat and power in Denmark, and demand response in the U.S.) demonstrate how energy systems can be integrated for more optimal operation. We need to systematically identify and develop many more of these opportunities at scale. Now is the time to develop these ESI solutions to address our energy challenges.