Executive Summary

The *Flexible Nuclear Energy for Clean Energy Systems* report provides a collection of technical analyses that, in the aggregate, demonstrate the current and potential future roles for nuclear energy in providing flexibility in meeting energy demands. For the purposes of this report, flexibility is defined as:

The ability of nuclear energy generation to economically provide energy services at the time and location they are needed by end-users. These energy services can include both electric and nonelectric applications utilizing both traditional and advanced nuclear power plants and integrated systems.

Power systems around the world are undergoing rapid and significant transformations. Driven by new cost-effective, low-emissions technologies and growing consensus on the need for economy-wide clean energy, the past decade has seen accelerated change and innovation in the ways that humans produce, transmit, and consume energy. These changes are only the beginning. The next decade will almost assuredly bring more innovation and change to advance the use of clean energy across all sectors in order to address multiple global challenges (e.g., universal energy access, energy security, economic recovery, environmental stewardship, climate resilience, and global health). As part of their individual energy transitions, countries are increasingly seeking ways to procure the flexibility needed to ensure reliable, affordable, and clean energy for their economies. Leveraging flexibility and diversity in energy system location, types of energy generation used, timing and scale of production, diverse energy applications, and multiple energy carriers and storage will be essential to achieving economy-wide clean energy transitions.

All energy assets can provide flexibility in some way. For example, aggregating and automating the operation of distributed resources, such as distributed solar photovoltaics (PV) or household appliances, using technology that did not exist a decade ago, is leading to entirely new business models and greater energy system flexibility. Nuclear energy is no different. Nuclear energy is experiencing rapid innovation, especially within the last decade. Nuclear energy is quickly increasing visibility for its existing and potential flexible properties alongside its traditional base load roles. While nuclear energy has constraints regarding how rapidly power can be maneuvered up or down, or how low of a power it can be operated at for an extended period of time, nuclear systems offer unique value to key types of system flexibility.

Today, nuclear energy already provides certain types of electric system flexibility on the megawatt (MW) to gigawatt (GW) scale in some countries. This flexibility is a valuable resource of clean energy but, to this point, nuclear energy has mostly been used for electricity production. Looking to the future, new innovations will provide ever-increasing types of flexibility from nuclear energy. Both existing and future nuclear plants are being re-imagined as novel sources of not only dispatchable electricity, but also thermal energy and chemical production, through novel integration with energy storage, conversion technologies, and hydrogen production. Several pilot projects are underway around the globe that will revolutionize and diversify the output of currently operating GW-scale systems.

Advanced Generation IV nuclear reactors[1] can be smaller, more distributed, and faster in changing their energy outputs. As a result, advanced reactors may have the opportunity to be designed to provide a host of novel electric and nonelectric energy services. In short, nuclear innovation has the potential to revolutionize clean energy systems.

This report reflects a collection of international experience and novel research from partner organizations of the Nuclear Innovation: Clean Energy Future (NICE Future) initiative. While the data and analysis presented may reveal differences among chapters due to individual authors' particular perspectives or focus, collectively they seek to explore the value of flexible nuclear energy. Looking across the chapters, several key points emerge that are summarized here at a high level.

There is already an established body of knowledge surrounding flexible operation of existing nuclear plants. Work in reactor physics, thermal hydraulics, and material science has demonstrated that nuclear reactors can safely provide flexible power output. Both research and operational data have contributed to a global body of knowledge on the subject. Several countries, including some featured in this report, have decades of experience in flexible operation of existing nuclear reactors. Additionally, multiple organizations have researched potential safety-related impacts of flexible nuclear operation. Their research has shown that flexible operation poses no known threats to nuclear safety. While some countries have significant experience in operating existing nuclear power plants flexibly, for other countries it may be difficult to adopt flexible operation that may require dedicated equipment and additional regulatory review and compliance. Existing reactors have the ability to provide flexible electricity output within established constraints that are a function of the reactor design. Additionally, flexibility has different implications for each country's power systems.

Innovation can increase the flexibility of existing nuclear reactors to produce both clean electricity and beneficial nonelectric products. Many organizations are researching how nuclear reactors can increase the speed with which they change their electrical output and diversify their energy products. Due to their large capacity and thermal output, operating nuclear reactors can support "bolt-on" enhancements or operational alterations to store energy for later use. Reactors can also provide thermal energy in addition to electricity to support production of diverse products such as hydrogen and chemicals. These enhancements could allow plants to operate continuously at their full rated power levels while flexibly supporting grid operations.

Advanced reactors will present even more opportunities for flexibility in nuclear systems. Despite the significant and valuable innovation occurring around existing GW-scale reactor systems, there are some energy services that only advanced reactors will be able to support. While some advanced reactors will be on the GW scale, many advanced reactor concepts could be built on the scale of 1–100 MW. These new reactor designs can be distributed to areas with smaller energy demand that cannot support traditional GW-scale plants, and some are being designed specifically to support these regions. Off-grid applications, such as providing heat and power to remote communities and industries (e.g., mining), are key examples of the types of uses that advanced reactors can flexibly support. Additionally, these designs can be coupled to novel energy

[1] For more information on Generation IV reactors, see Chapter 13.

storage systems, such as thermal energy storage or hydrogen production, to further increase flexibility.

Nuclear flexibility can be key in enabling other clean energy generators. Clean energy sources have seen rapid innovation and cost reduction in the last decades. While solar PV and wind power are two of the most commonly cited, other energy sources such as distributed run-of-the-river hydropower, dispatchable geothermal (both deep and shallow), biomass, concentrating solar power, and fossil energy with carbon capture have also experienced rapid technological and economic advances in the last decade. Each advancement in energy generation technology requires engineers and policymakers to re-imagine and broaden their views on possible energy interconnections. Nuclear energy has the potential to couple with many other energy sources in a synergistic fashion that results in integrated systems that are more than the sum of their parts.

The clean energy systems deployed by each country will depend on local natural resources, geography, topology, infrastructure, and societal values. The Clean Energy Ministerial's (CEM's) mission is to facilitate clean energy transitions by sharing diverse international experiences. Accordingly, the NICE Future initiative invites energy ministers to re-examine the opportunities and potential benefits offered by nuclear energy, whether or not nuclear energy is currently part of their energy systems. This report provides information on flexible nuclear energy operation and innovations that will be valuable for economy-wide clean energy transitions in those countries that choose to realize them.