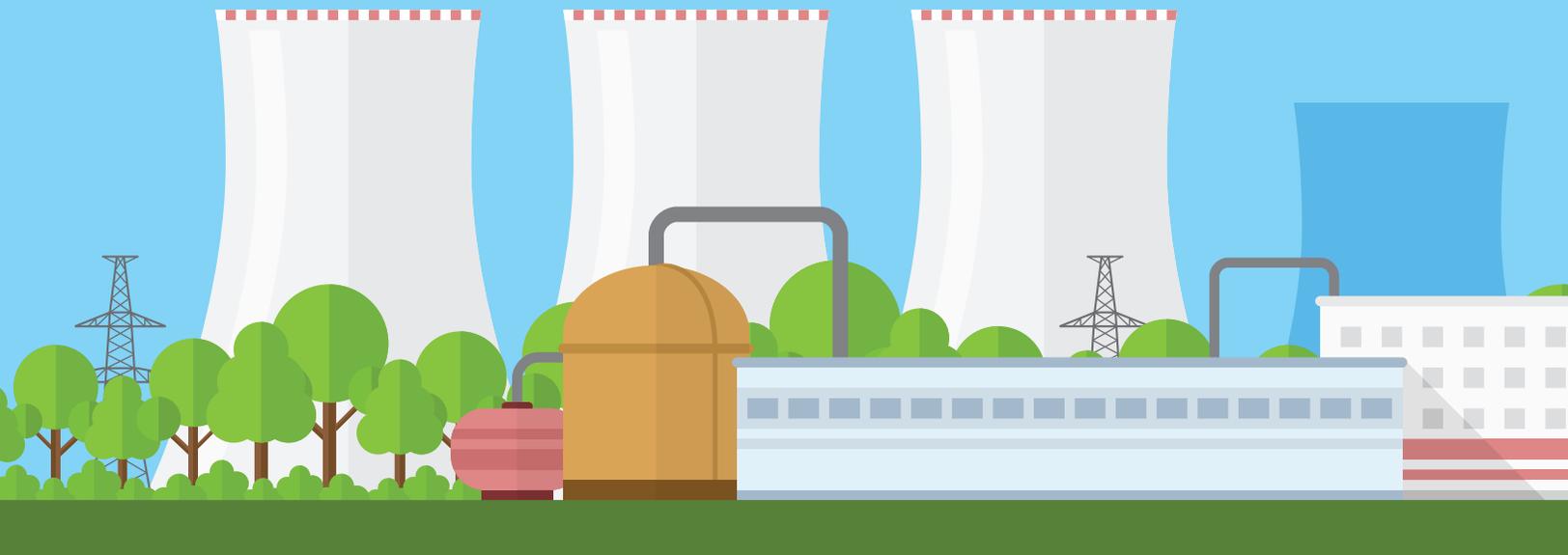


The Nuclear Option

for Meeting the Grand Challenges of the 21st Century



This article considers the role of nuclear technology in the 21st century for meeting energy needs and addressing environmental and resource concerns in the United States.

Access to reliable and affordable electricity is a hallmark of the developed world and is all too often taken for granted when reaching for the light switch at nightfall, adjusting the thermostat downward in summer, or powering the expanding collection of consumer electronic devices that have become essential to daily life. Today, nuclear power plays an important role in the generation and delivery of reliable electricity in the United States and other nations.

With extremely high energy density, nuclear plants only require partial refueling at 18–24-month intervals. With best-in-class availability, nuclear power offers on-demand power 24 hours a day, 7 days a week. As a result, nuclear power can provide both the energy and capacity to support and stabilize electricity grids grappling with intermittent generation sources and evolving consumer needs that are driving peak demand and supply further out of phase with one another.

Most importantly for climate programs, nuclear power generation is essentially carbon free,¹ accounting for almost two-thirds of the carbon-free electricity generation in the

United States.² Together, this combination of scalable energy and favorable environmental footprint is unique and valuable among energy options as society faces the collision of increasing populations, increasing energy demand, and increasing pressures on limited natural resources.

Forecasts and modeling from many independent entities tend to converge around a common theme—climate change mitigation goals cannot be met without a comparable if not expanded role for nuclear power. A clear path to societal carbon emission reductions exists through decarbonization of the economy. But decarbonizing the electricity sector alone is not sufficient given the significant contributions from non-electric sectors. The fossil fuel-reliant transportation sector alone represents 37 percent of the total energy use in the United States and offers a ripe target for decarbonization through electrification or fuel substitution. Challenges become even more daunting and the potential role for nuclear increases if important technologies like grid-scale energy storage and carbon capture and sequestration do not come to fruition.

Coming to Terms with Terminology

As with all technical subjects, discussion of nuclear technology includes many specialized terms and jargon that will be foreign to outsiders. It is worthwhile introducing and defining some of the more essential terms.

Light Water Reactors (LWRs): LWRs are reactors that use ordinary water to slow down (moderate) neutrons and to remove heat from the reactor core. The U.S. nuclear fleet is comprised exclusively of this type of reactor in one of two forms: boiling water reactors (BWRs), in which water is allowed to boil and steam is produced directly in the main or primary circuit of the reactor; and pressurized water reactors (PWRs), in which boiling is suppressed and steam is produced outside of the primary system of the reactor.

Advanced Light Water Reactors (ALWRs): ALWRs are LWRs that incorporate evolutionary design improvements for safety- and performance-based technology improvements, contemporary regulatory requirements, increased expectations from owner-operators, and more than five decades of operational experience. ALWRs belong to Generation III of the nuclear family tree and comprise the majority of nuclear plants under construction today.

Small Modular Reactors (SMRs): SMRs are reactors that have been designed with lower power output and smaller physical dimensions to realize benefits of lower unit costs, factory-based manufacturing, and modular transportation and construction. The more mature SMR designs are generally scaled-down and simplified versions of PWR technology and are leading the way to commercial deployment. Used alone, the term SMR generally refers these small modular LWRs. However, since “small” and “modular” are not technology specific, SMR can also encompass other reactors designs, such as more advanced Generation IV reactors.

Advanced Reactors: Advanced reactors are reactors that employ fuel, coolants, and technologies that generally extend beyond reactor designs that are currently operating. Recognizing that the term advanced can also refer to LWRs and SMRs, here the term is used in a more restrictive sense. Advanced reactors also offer substantial improvements in natural resource utilization, inherent safety, economics, proliferation resistance, and security. In this regard, the terms “advanced reactor” and Generation IV (GEN IV) are often used interchangeably. Most advanced reactor concepts employ coolants/heat transfer fluids other than liquid water for improved design and performance benefits such as higher operating temperatures and lower (even ambient) operating pressures.

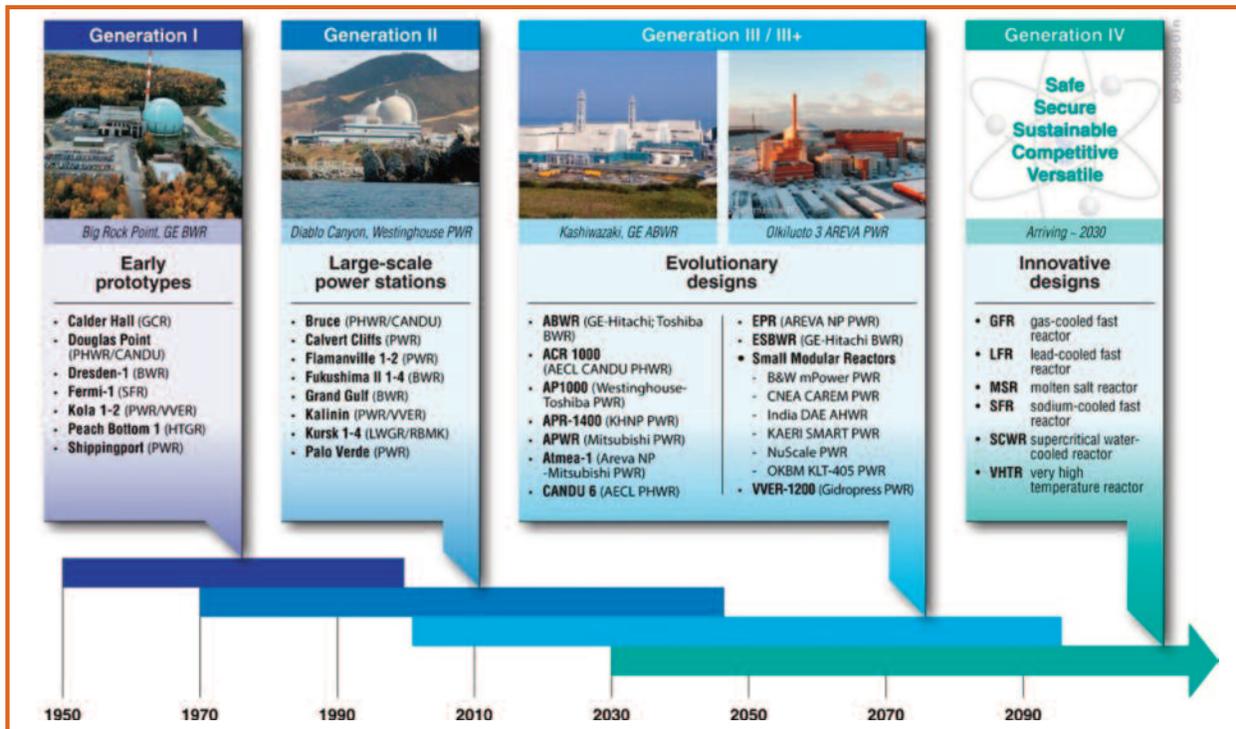


Figure 1: Evolution and description of commercial nuclear power reactors by technology generation.

Source: Generation IV International Forum, 2015; <https://www.gen-4.org/> (accessed September 2015).

With over a half-century of nuclear power generation behind us and a slate of challenges and potential options before us, what is the role of nuclear technology in the 21st century for meeting energy needs and addressing environmental and resource concerns in the United States? Is nuclear destined to succumb to mounting economic challenges and ever present waste, security, and proliferation concerns? Or is a new golden age just around the corner?

Nuclear Genealogy

The family tree for fission-based commercial nuclear power reactors can be grouped into generations. Instead of Baby Boomers, Gen-Xers, and Millennials, reactor generations are designated numerically based on historical timeframe and technology, as shown in Figure 1.

Generation I encompasses the earliest period of commercial nuclear power.³ **Generation II** comprises the nuclear plant designs constructed during a period of rapid expansion of nuclear power and increasing power levels of reactors spanning the late 1960s and through the 1990s, with the crowd of early concepts thinning to a handful of designs dominated by LWR technology derived largely from naval propulsion program in the United States.

With poor nuclear plant performance and the Three Mile Island accident in 1979, nuclear plant owner-operators drove

the nuclear market toward a new generation of designs emphasizing safety and economics through greater simplicity, standardization, and regulatory pre-approval of designs.⁴

These **Generation III** nuclear reactors incorporate evolutionary design improvements on prior commercial technologies based on five decades of experience and include large advanced light water reactors (ALWRs) and small modular light water reactors (SMRs).

Generation IV (GEN IV) advanced fission reactors generally offer significant improvements with respect to current nuclear technologies in terms of potential for enhanced resource utilization, inherent safety, economics and proliferation resistance and security.⁵

Table 1 presents key properties and features of the GEN IV concepts that illustrate the wide range of attributes offered by the next generation of reactor technologies. Use of coolants other than water can offer a number of features such as reduced corrosion and much larger safety margins due to higher boiling temperatures and higher heat capacities than water. Higher outlet temperatures can permit potentially higher electrical generation efficiency and access to new markets and missions, such as combined heat and power and sale of high value steam to petroleum and chemical refiners. Lower pressures can mean less costly reactor components and significantly enhanced safety. Reactors that

employ more energetic (or fast) neutrons open the door to fuel resource amplification by effectively creating more fuel than consumed via the process known as “breeding”.

The Role of Nuclear in the United States Today

Nuclear provides one-fifth of electricity generation in the United States today (see Figure 2 inset) from 100 reactors at 61 sites.⁶ Nuclear also plays a broader, albeit less visible, role in the U.S. power system as it currently represents almost two-thirds of non-carbon-emitting generation.⁷ Further, nuclear power provides the inertia and energy density needed to stabilize operation of the complex network of wires and transformers that supply electricity to customers, known collectively as “the grid”, as the penetration of intermittent renewables and distributed generation increases.

The current 20-percent contribution from nuclear power also belies a remarkable story of improvement and performance. The number of U.S. operating plants peaked in 1990 at 112 around the same time nuclear first reached its one-fifth share and has since declined somewhat due to retirements. Yet absolute nuclear electricity generation has increased substantially over the past 25 years following the end of nuclear plant construction in the United States (Figure 2 black solid line, left-hand axis).

This counterintuitive trend is the result of an industry “doing more and better with less.” Increased oversight and improved

maintenance of the U.S. nuclear fleet post-Three Mile Island resulted in dramatic improvements in both plant safety and performance, allowing utilities to squeeze more electrical output from a smaller fleet through a combination of regulator-approved increases in power output from individual reactors known as power uprates and increases in the fraction of time reactors actually generated electricity in a year (i.e., the capacity factor; Figure 2 blue dotted line, right-hand axis).

What Happened to the U.S. Nuclear Renaissance?

A decade or so ago, the words “nuclear” and “renaissance” were frequently found together in print and in conversation. Expectations had been raised in the industry and among the public of a new fleet of ALWRs built to meet increasing electricity demand, while also addressing climate change concerns through avoidance of continued growth in carbon dioxide emissions.

Over a three-year period from 2007 to 2009, the U.S. Nuclear Regulatory Commission (NRC) received applications for construction and operation of 28 new reactors.⁸ But the arrival of cheap shale gas, a lack of carbon pricing, and historic global economic downturn soured the economics for nuclear generation in many parts of the United States, especially deregulated electricity markets.⁹ A third of the applications were subsequently withdrawn, leaving 19 units officially listed as under active NRC review. Of these, four ALWRs are under construction and nearing completion in Georgia and South Car-

Table 1. The Six Advanced Reactor Concepts Recognized by the Generation IV International Forum.

Reactor Concept	Coolant	Outlet Temperature (°C)	Pressure	Neutron Spectrum
Gas-cooled fast reactor (GFR)	Helium	850	High	Fast
Lead-cooled fast reactor (LFR)	Lead (metal) or Lead-Bismuth (eutectic)	500–800	Low	Fast
Molten salt reactor (MSR)	Fluoride salts	700–1,000	Low	Fast or Thermal
Sodium-cooled fast reactor (SFR)	Sodium (metal)	500–550	Low	Fast
Supercritical-water-cooled reactor (SCWR)	Water ^a	500–625	Very High	Fast or Thermal
Very-high-temperature reactor (VHTR)	Helium	700–1,000	High	Thermal

Note: ^aWater exits reactor in a super-critical (i.e., more gas-like) state.

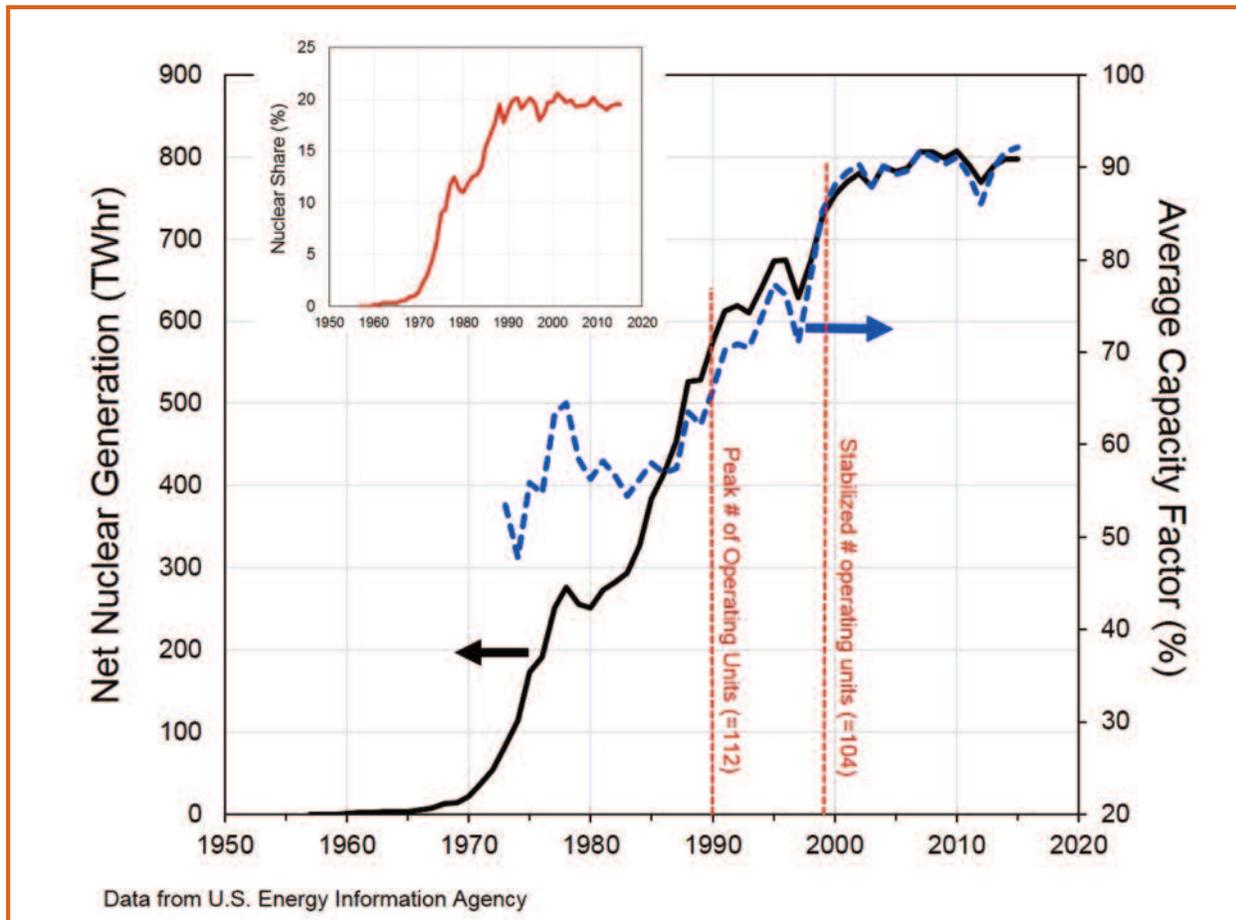


Figure 2: U.S. nuclear utilities have maintained a 20-percent nuclear electricity share (inset) and increased net electricity generation (left axis) even as the number of nuclear units has decreased slightly from the peak through power uprates and increased plant availability.

olina. Meanwhile, previously halted nuclear plant construction on Watts Bar 2 in Tennessee was resumed and finally completed in 2015.

Punctuating these adverse developments, the accident at Fukushima Daiichi in Japan in March 2011 marked the end of global nuclear exuberance, as several European countries reinstated nuclear phase outs and moratoriums; nuclear operators implemented costly enhancements based on the lessons learned from the event; and Japan saw one third of its electricity supply go offline for an extended period of uncertain length.

Yet, in spite of economic challenges and the aftermath of Fukushima Daiichi, construction of new large LWRs has continued, primarily in the China and other Asian countries, along some non-LWR designs (see Figure 3). Development of smaller, more affordable light-water SMR designs continues as well, although investment and market interest has been tempered in the post-2008-recession period. Two SMRs are currently under construction, one in Argentina (CAREM-25)

and one twin unit in Russia (KLT- 40S).

In the United States, NuScale Power is on track to submit its integral pressurized water SMR design to the NRC in late 2016 as a key step toward commercial deployment.^{9b} Meanwhile, western U.S. utility consortium, Utah Associated Municipal Power Systems, is moving ahead with plans to build the first-of-a-kind multi-unit NuScale power plant on a site at the Idaho National Laboratory to supply power to the grid for its customers.^{9c}

The Quest for Options

Increasing industry and government interest in advanced, non-LWR reactors has coincided with unprecedented influx of private investment exceeding \$1 billion in a growing field of entrepreneurial developers.^{10,11} A primary driver for renewed interest in advanced reactor technology among utilities is the desire for scalable generation options in the 2030–2050 timeframe to address the looming retirement of traditional baseload capacity (especially coal and nuclear), while meeting future energy demand and hedging against uncertainty

resulting from policy, regulatory, and market changes. While electric power utilities are generally considered to be a very conservative bunch influenced heavily by near-term factors such as fuel costs and electricity prices, they also are driven to look out in the future to balance longer range strategic interests against shorter term business imperatives in the form of integrated resource planning. Given costs in the billions of dollars and lead times of a decade or more, financing, siting, licensing, and construction of new infrastructure like plants and transmission lines requires advanced planning to enable allocation of resources.

When utilities look to the future now, they see a daunting collection of challenges for supplying safe, reliable, affordable, and environmentally responsible electricity enveloped in a gathering storm of uncertainty related to carbon emission policy, natural gas prices, penetration of distributed, intermittent renewable generation, the availability (or lack) of viable grid-scale energy storage, electricity market reform, and other unknown changes to markets, regulation, and policy. Any one of these factors can have a major disruptive effect on the viability of a specific electricity generation resources, as evidenced with the introduction and rapid dominance of shale gas.

As a result of shifting market, regulatory, and policy conditions, nuclear and coal find themselves at odds with the new order. Over the last decade, the contribution of coal to electricity generation in the United States dropped from one half to one third, due, in large part, to price competition from other sources and tightening environmental regulation (see Figure 4). This decrease has been largely offset by increases in natural gas

generation and, to a lesser degree, increased penetration of renewables from 2 percent to 7 percent.

The Future Role of Nuclear Generation

Projections of increasing global electricity demand associated with economic growth and proposed large-scale decarbonization of industrialized economies for climate change mitigation indicate continuing growth in nuclear generation throughout the 21st century. The Organization for Economic Cooperation and Development (OECD) issued a nuclear technology roadmap that proposed a “2DS” scenario for limiting global warming to 2 °C through decarbonization of all energy sectors.¹² The roadmap calls attention to the anticipated need for nuclear generation capacity that more than doubles from just under 400 GWe in 2015 to approximately 930 GWe in 2050.

In March 2015, the United States submitted its target reductions for emissions of greenhouse gases (GHGs) to the United Nations Framework Convention on Climate Change (UNFCCC) ahead of the 2015 Paris Climate Conference (COP-21). This voluntary pledge, known as the Intended Nationally Determined Contribution (INDC), calls for reductions of U.S. net GHG emissions by 26–28 percent below 2005 levels by the year 2025 and an aggressive goal of an 80-percent reduction in GHG emissions over the entire U.S. economy by 2050.¹³ A path to this 80-percent economy-wide reduction is difficult if not impossible to imagine without a substantial increase in electrification and fuel substitution supported by substantial growth in nuclear energy in the 2030–2050 timeframe.

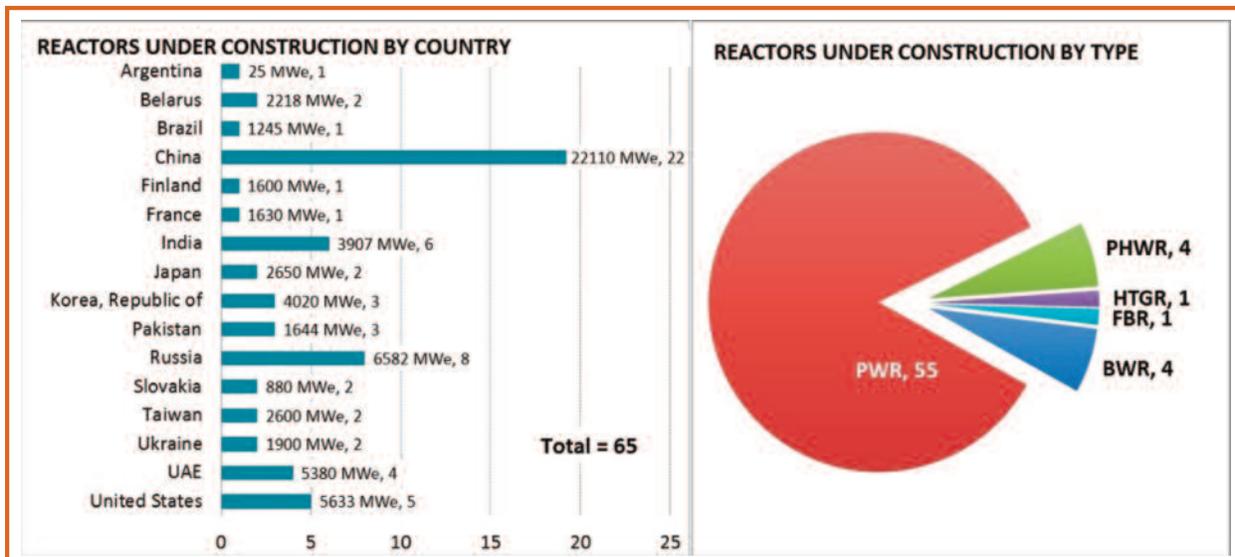


Figure 3: Global picture of new commercial nuclear reactors under construction by country (left) and by type (right). Data from IAEA PRIS Database (updated May 16, 2016).

Notes: PHWR = pressurized heavy water reactor; HTGR = high-temperature gas-cooled reactor; FBR = fast breeder reactor; BWR = boiling water reactor; PWR = pressurized water reactor.

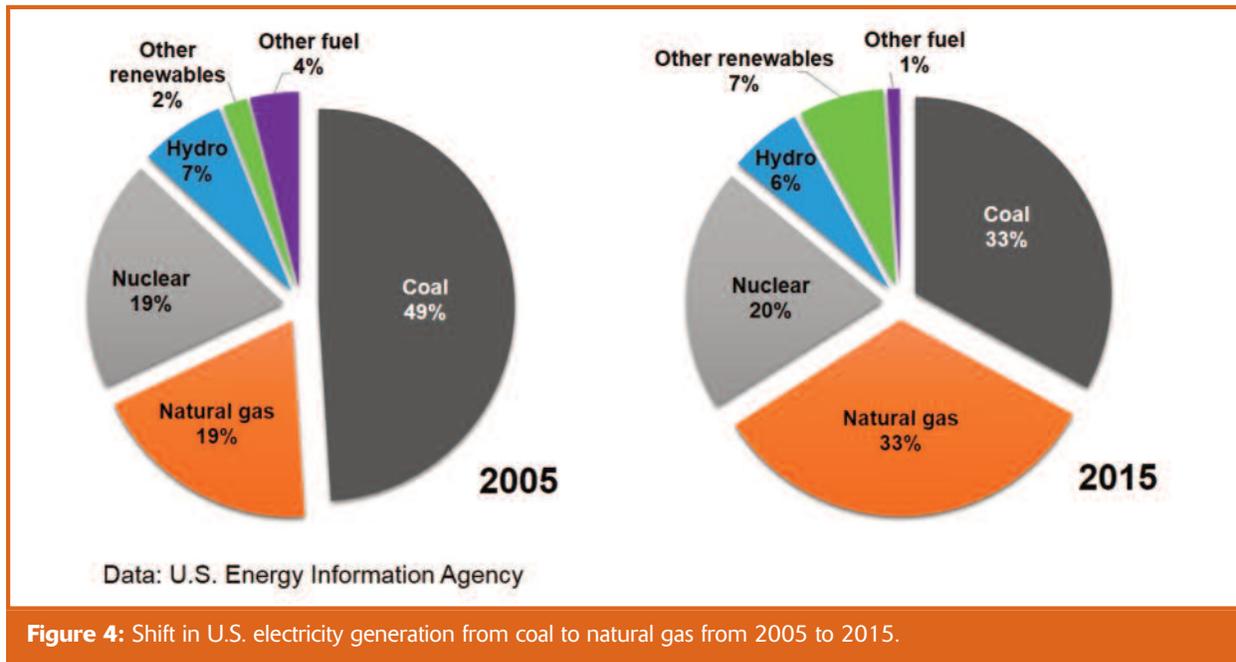


Figure 4: Shift in U.S. electricity generation from coal to natural gas from 2005 to 2015.

Energy supply forecasts and planning, including the U.S. INDC and the Clean Power Plan, generally assume continued contribution of nuclear power generation at current levels for the foreseeable future. Yet, as illustrated in Figure 5, this assumption is itself questionable as the current 60-year operating licenses will need to be extended to prolong the operation of the U.S. nuclear fleet to prevent a precipitous decline in this non-GHG emitting capacity (red line). Moreover, even for the case where operation of current reactors is extended to 80-years (blue line), new nuclear capacity or accelerated growth in other GHG-free energy sources by 2050 will be required to meet current U.S. climate emissions targets.

Internationally, increasing nuclear generation capacity is projected for markets in China, India, the Middle East, and Russia. Nuclear growth in the OECD countries (including the United States and European Union) will remain flat in the near-term. Importantly, flat growth in developed economies will still involve substantial installation of new nuclear capacity to keep pace with retirements.

The scale of investment needed to replace aging energy infrastructure is immense, measured in trillions of dollars. Investment need for energy infrastructure in general in the United States is projected to be on the order of \$3 trillion over next 10 years. Globally, the figure is an estimated \$1.6 trillion per year. The International Energy Agency (IEA) concluded in its 2014 special report, *World Energy Investment Outlook*, that \$48 trillion in global investment is needed through 2035 to meet projected energy needs, of this total nuclear represents \$1 trillion.¹⁴ While nuclear represents a small fraction of the total world's energy infrastructure investment, the absolute sums involved are substantial. The

IEA projection of 930 GWe of installed global nuclear capacity by 2050 for its 2DS (i.e., limiting global warming to 2 °C Celsius temperature increase by 2050) climate stabilization scenario corresponds to new investment in nuclear of \$4.4 trillion.¹⁵

The opportunities and timeframes associated with nuclear growth in the United States include the following potential timelines and roles for nuclear out to 2050 and beyond (Figure 5):

- In the near-term (i.e., within the next decade), options for the introduction of new nuclear capacity are likely limited to life extension of the operating fleet and modest additions of large GWe-class Generation III LWRs like those nearing completion in Georgia and South Carolina.
- Over the medium-term (2020s), expanding construction of SMRs for applications where small modular aspects are compelling and large ALWRs are not practical or economic.
- Longer-term (2030s and beyond) could see the introduction of advanced GEN IV design concepts deployed as non-emitting energy alternatives to the use of fossil fuels in both stationary and transportation applications.
- Beyond the 2050s, the widespread introduction of fast reactors and a supporting U.S. infrastructure would enable virtually unlimited extension of natural uranium (and thorium) fuel resources via continuous recycling of nuclear fuel. Uranium resources are currently not limiting.¹⁶

Opportunities and need for all nuclear (ALWRs, SMRs, and GEN IV) increase substantially if decarbonization of industrial and transportation sectors is seriously pursued via economy-

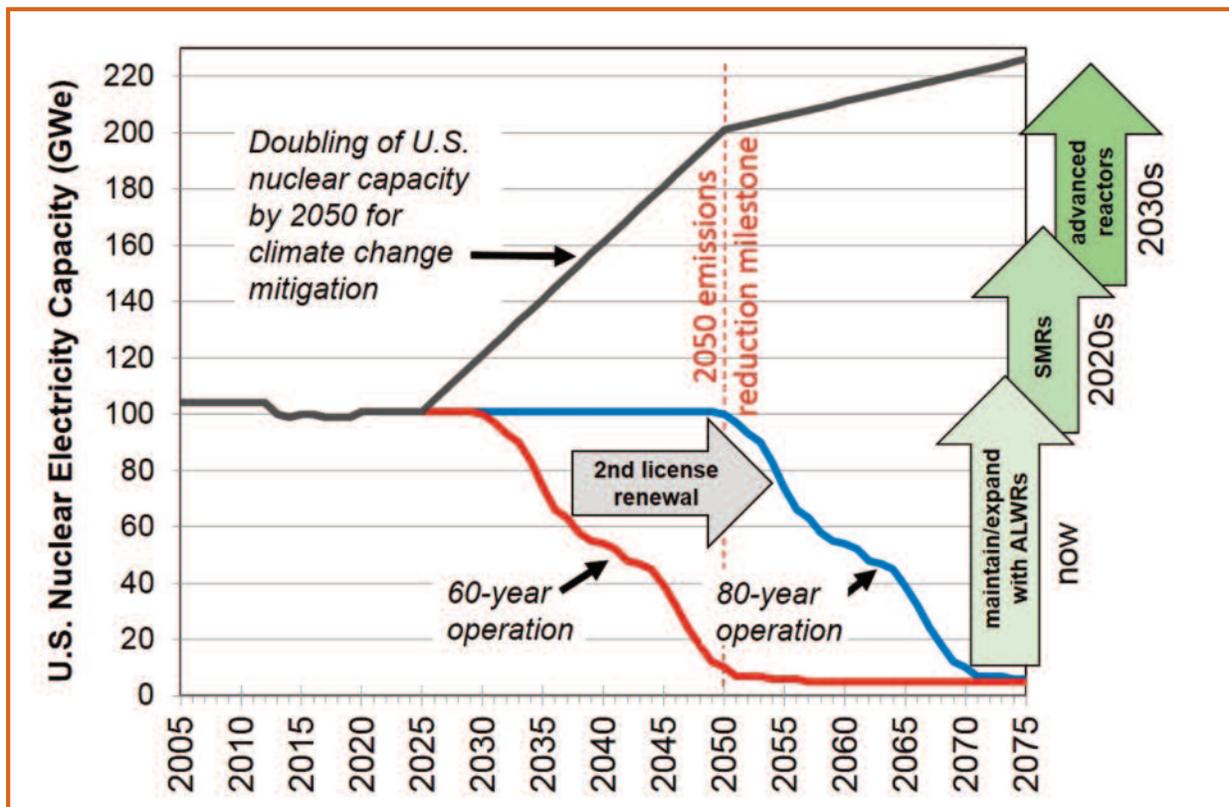


Figure 5: Projected U.S. net nuclear electricity generation capacity (GWe) for the current fleet operating to 60 years (red line) and to 80 years (blue line). In addition, the figure illustrates what doubling of U.S. nuclear electricity capacity looks like relative to the existing fleet to meet greenhouse gas emission reduction targets. The generation gap widens between operating plants and future targets if new capacity from large ALWRs, SMRs, and eventually advanced reactors is not added in a timely fashion.

wide electrification and fuel substitution (e.g., hydrogen for petroleum). Both SMRs and GEN IV reactors offer unique features and attributes, including substantial increases in safety, to support new applications and disruptive business cases through greater operational, deployment, and product flexibility not available from current technology.¹⁷

What About Waste?

Management of used nuclear fuel and other long-lived radioactive wastes associated with nuclear energy production is often portrayed as an intractable problem that precludes consideration of nuclear energy as an environmentally responsible and sustainable technology option. However, such assertions run counter to a solid international consensus built on six decades of scientific and engineering study on the appropriateness and capability of deep geologic disposal for providing the long-term protection of humans and the biosphere from the hazards of used fuel and high-level radioactive wastes.¹⁸

All forms of energy generation are burdened with life-cycle impacts and environmental footprints, and the current challenge of climate change mitigation is the result of energy

choices that failed to internalize the costs and impacts of by-products. In this respect, nuclear energy uniquely offers the opportunity to capture and manage its by-products and wastes in a very compact and manageable form. On a per-unit energy basis, this ends up being the inescapable “no free lunch” dilemma—one has to choose between dilute wastes like carbon dioxide, large physical and lifecycle footprints associated with low-density energy sources like wind and solar, or concentrated radioactive wastes from nuclear.

Security and Proliferation Concerns

As with the nuclear waste issue, the security and proliferation concerns associated represent an important aspect of nuclear energy that must be addressed. While much is often made of the ability of new technologies to solve the problem of securing nuclear material and technology and discouraging development of new state-sponsored weapons programs and diversion of the same material and technology for use by non-state actors, there is no “silver bullet.”¹⁹ All nuclear programs, materials, and technologies require competent management, adequate protection, and effective oversight in the form of national regulation and international institutions and safeguards regimes.²⁰

Navigating Uncertainty for Developing and Maintaining Nuclear Energy Options

Developing a meaningful strategic vision for nuclear energy's role in the 21st century energy mix requires acceptance of large uncertainties and reconciliation of disparate and often conflicting trends. In the United States, one trend finds safe, reliable, non-emitting nuclear plants struggling for survival in markets with low electricity prices, limited demand growth, and inadequate valuation of ancillary services like grid stabilization. With this trend comes the risk of early plant closures and limited life extensions beyond 60-years for the current operating fleet and a pessimistic outlook for construction of new nuclear capacity.

A second important and opposing trend indicates an increasing need for reliable, dispatchable, high-quality electricity to

counterbalance the mounting effects of increasing penetration of intermittent renewables and distributed generation. When paired with aggressive proposals for wholesale decarbonization of the U.S. economy via electrification or fuel substitution (e.g., with hydrogen), this second trend makes a future energy portfolio dependent on sustained contributions from nuclear energy—more so if other enabling technologies such as carbon capture and sequestration and grid-scale energy storage fail to materialize. In the face of such uncertainty, existing and advanced nuclear technologies offer utilities and other stakeholders perhaps the most valuable of all commodities for the future: options. However, such options must be developed and maintained through adequate planning and investment to ensure they are ready when and at the scale needed. Whether this occurs is perhaps the biggest uncertainty of all. **em**

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Notes and References

1. A generation technology is only carbon free to the extent that all aspects of its life-cycle, including manufacturing, construction, transportation, and fuel cycle activities, are carbon free.
2. The Nuclear Energy Institute (NEI) reports a 63-percent nuclear share of U.S. carbon-free electricity generation based on 2014 U.S. Energy Information Agency (EIA) data.
3. The first nuclear electricity was generated by a sodium-cooled fast reactor (EBR-I, 1951), and the first truly commercial nuclear power plant was a gas-cooled, graphite-moderated reactor in the UK (Calder Hall 1, 1956).
4. Two Generation-III reactors, advanced boiling water reactors, were built and operated at the Kashiwazaki-Kariwa nuclear plant in Japan; four are nearing completion in the United States; and many more are under construction in China, Finland, France, South Korea, and the United Arab Emirates.
5. Strictly speaking, the term Generation IV refers to the six advanced reactor design classes designated under the Generation IV International Forum (GIF). See *A Technology Roadmap for Generation IV Nuclear Energy Systems*; GIF-002-00, 2002.
6. Of these 100 reactors, 66 are PWRs and 34 are BWRs. This total includes Watts Bar 2, a Generation II PWR completed, commissioned and licensed to operate in 2015, and grid-connected in June 2016.
7. 62.9 percent in 2014 according to Nuclear Energy Institute and U.S. Energy Information Agency data.
8. Source: Combined License Applications for New Plants; U.S. Nuclear Regulatory Commission, Updated February 2016 (accessed April 2016); available online at <http://www.nrc.gov/reactors/new-reactors/col.html>.
9. The United States is not a single electricity market, but rather comprises multiple regional markets in which prices are set via competitive or cost-of-service or competitive model.
- 9b. Source: Pre-Application Review of the NuScale Design; U.S. Nuclear Regulatory Commission, Updated June 2015 (accessed June 2016); available online at <http://www.nrc.gov/reactors/advanced/nuscale/review.html>.
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19. Bathke, B. The Attractiveness of Materials in Advanced Nuclear Fuel Cycles for Various Proliferation and Theft Scenarios. In *Proceedings of Global 2009, Paris, France, September 6-11, 2009*.
20. For example, conclusions from a recent comprehensive, U.S. Department of Energy-sponsored nuclear fuel cycle options evaluation found that security and proliferation resistance criteria do not provide meaningful discrimination among technology options, all present vulnerabilities and risks that require appropriate intrinsic and extrinsic controls. See *Nuclear Fuel Cycle Evaluation and Screening – Final Report*; FCRD-FCO-2014-000106; U.S. Department of Energy, October 8, 2014.