Fall 2020

NUCLEAR ENERGY REVISITED

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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NATIONAL ACADEMY OF ENGINEERING

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The
BRIDGE

NATIONAL ACADEMY OF ENGINEERING

Editor in Chief: Ronald M. Latanision
Managing Editor: Cameron H. Fletcher
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The Bridge (ISSN 0737-6278) is published quarterly by the National Academy of Engineering, 2101 Constitution Avenue NW, Washington, DC 20418. Periodicals postage paid at Washington, DC.

Vol. 50, No. 3, Fall 2020

Postmaster: Send address changes to *The Bridge*, 2101 Constitution Avenue NW, Washington, DC 20418.

Changes of address or requests to unsubscribe should be sent to PGibbs@nae.edu.

The Bridge is printed on recycled paper. ♻

Mission Statement of *The Bridge*

The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7,000, including NAE members, members of Congress, libraries, universities, and interested individuals all over the country and the world. Issues are freely accessible at *www.nae.edu/TheBridge*.

A complete copy of *The Bridge* is available in PDF format at *www.nae.edu/TheBridge*. Some of the articles in this issue are also available as HTML documents and may contain links to related sources of information, multimedia files, or other content.

The BRIDGE

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LINKING ENGINEERING AND SOCIETY

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The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. John L. Anderson is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.nationalacademies.org**.

Editor's Note

The NAE and *The Bridge* Address Changes

Ronald M. Latanision (NAE) is a senior fellow at Exponent.

In this issue we welcome new NAE Chair **Donald C. Winter**, former president and CEO of TRW Systems and secretary of the Navy in the Obama administration. He and President **John Anderson**, whose column President's Perspective has appeared in previous issues, will share this space, alternating from one issue to the next, as a vehicle for exploring issues of interest to the engineering community and NAE members. In his inaugural column, Don writes of the clear need today for the NAE to provide the "independent, objective, and nonpartisan advice" that is our mission in service to society and the nation.

We are living in profoundly unsettling times. The world and particularly this nation are struggling to control and contain a pandemic the likes of which few living Americans have ever experienced. And the persistent struggle with inequities and racial injustice in this country has been vividly brought to national attention through shocking videos, lawful protests and marches, and the passing of civil rights icon John Lewis. The NAE has a role to play in addressing these and other issues of broad concern. As a start, President Anderson has established a new Committee on Racial Justice and Equity to advise the NAE, described on p. 82.

We also include in this issue a personal message from a member of both the NAE and NAM, **Rod Pettigrew**, who last year won the NAE's Arthur Bueche Award for his contributions to technology research, policy, and national and international cooperation. Rod is executive dean for engineering medicine and CEO of EnHealth (Engineering Health) at Texas A&M University. As a Black man who grew up in this country, Rod has a deep and personal understanding of racial injustice. His view, based on his experiences, could lead us to a better world: "When people learn that our shared humanity binds us one to the other, that differences which do not involve character actually bring character to our interwoven lives, that is when our society will honor its stated commitment to life, liberty, and the pursuit of happiness for all." I appreciate Rod's generosity in sharing his experiences and outlook. His testimony is sure to open some eyes and I hope will help guide thinking and actions as we all navigate and create more respectful and equitable ways going forward.

In the summer issue, we published a paper dealing with climate change by high school junior Nicholas Margiewicz of North Port, Florida. I am inclined to the view that we should hear from young people addressing issues facing our nation and the world. In this issue, we include a piece from Matt Fitzgerald, a graduate student at the University of Colorado studying under Brandon Schaffer, a former state senator. The paper explores ways to keep voting outcomes safe from foreign intervention and cyberattacks. This could not be more timely, and it is encouraging to me that once again young people are stepping up to the realities of contemporary life and considering solutions to important problems.

And I am delighted that a public webinar was held in August based on the summer issue's articles on aeronautics. Featuring many of the issue's contributors, the session was a joint effort with a new NAE program, the Forum on Complex Unifiable Systems (FOCUS).

In the winter issue Guru Madhavan, **William Rouse**, and George Poste coedit a compendium of topics derived from a well-attended FOCUS convocation held in April. That issue will be a companion to a special issue celebrating the 50th anniversary of *The Bridge* as an NAE publication. The anniversary issue will feature 50 short essays that look forward to the next 50 years of engineering and technology in the service of society.

As always, I welcome your comments and feedback at rlatanision@exponent.com.

RM Latanision

A Word from the NAE Chair

Independent, Objective, and Nonpartisan Advice in the 21st Century

Donald C. Winter

This is my first opportunity to address the readership of *The Bridge*, one that comes as I start my term as chair of the NAE. I have been blessed with a full and diverse career as an engineer. Now in my failed retirement, I find that I have one more opportunity to follow Gordon England (we were the 73rd and 74th secretaries of the Navy) and give back to the engineering community and the nation.

NAE president John Anderson and I will alternate authorship of this column. His previous two columns addressed challenges to the engineering profession posed by climate change[1] and by the covid-19 pandemic.[2] While both of these phenomena are widely recognized as two of the most significant challenges confronting society and the world today, their profound implications for the engineering profession are not generally understood. Yet engineering has a critical role to play in addressing them, from how to mitigate the effects of climate change to how to evolve engineering education during and hopefully after the pandemic lockdowns.

This is a challenging time and the NAE's role as an advisor to the federal government on matters of engineering and technology is of increasing import. The Academies have a distinguished history of providing advice to the government since the establishment of the National Academy of Sciences in 1863 and the National Research Council in 1916. In carrying out their responsibility to address questions of national significance, the Academies call on the nation's preeminent experts in science, engineering, and medicine. "Our reports are viewed as being valuable and credible because of the institution's reputation for providing independent, objective, and nonpartisan advice with high standards of scientific and technical quality."[3]

There is, however, a major limitation in this process: in most cases, the Academies must first be asked for that advice and provided with the needed funding. While study committee members serve pro bono, they are reimbursed for their expenses, which can be considerable, particularly when travel is required. Furthermore, staff support is necessary to guide the study process according to the exacting NRC processes that ensure independence, objectivity, and substantiation of all study results. And "clients" need to recognize the need for advice. While many government leaders understand and value the advice from the Academies' expert committees, it is increasingly evident that there are a number of issues for which that "independent, objective, and nonpartisan advice" would materially promote national security and welfare,[4] but that are not tasked or funded.

Arguably the simplest way to address this dilemma is for the NAE to take the initiative and self-fund programs and consensus studies to address critical national issues. To do so requires discretionary funding, and this funding must come from donations. We are fortunate that a few significant donations in the past few months will enable us to proceed in this direction in a limited manner. More are needed.

The need is clear, as is the opportunity for the NAE to help the nation and society at large. The NAE's ability to do that depends on the willingness of the NAE membership and supporters to contribute and participate actively in ongoing and future efforts. I look forward to working with you throughout my tenure on this and other challenges and opportunities for the NAE.

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[1] https://www.nae.edu/228958/Presidents-Perspective-Climate-Change-A-Call-to-Arms-for-the-NAE

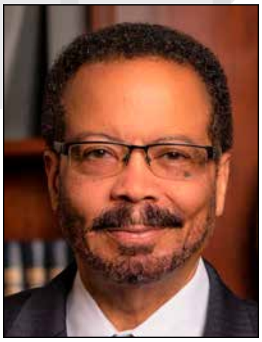
[2] https://www.nae.edu/234456/Presidents-Perspective-Microscopic-Assault-on-Humanity

[3] https://www.nationalacademies.org/about/our-study-process

[4] http://nasonline.org/about-nas/history/archives/milestones-in-NAS-history/organization-of-the-nrc.html

Member Reflection

Humanity Binds Us



Roderic I. Pettigrew (NAE/NAM) was founding director of the NIH National Institute of Biomedical Imaging and Bioengineering (NIBIB) and is now CEO of Engineering Health (EnHealth) and executive dean for Engineering Medicine (EnMed) at Texas A&M University and Houston Methodist Hospital.

Many were appalled to observe the Central Park incident where a woman used the ethnicity of a peaceful bird watcher and a 911 call in a failed effort to subjugate him based on his color. However, this incident was actually a service to the nation because it unveiled just how pervasive racism is in our society. As a majority person, the woman knew that this country's core racism is so systemic and its actuation so predictable, she could easily weaponize it. She knew that there is an imbalance of power based purely on a trivial difference in skin tone. If ever there was a question about this attitude and behavior existing broadly in our society, the Central Park incident answered it: It exists, it is real, and it has resulted in multiple shocking deaths and other injustices that the world has now witnessed in anguish.

When the death of Houstonian George Floyd was observed, his torture at the knee of a purveyor of this naked truth was just too much to bear. When George took his last breath, so did the national tolerance for the societal ill that took his life and the lives of many before him.

This disregard for the basic humanity of minorities is a bear of a problem. It happens to people simply born with darker skin tones and affects them for all of their lives. In some way or form, it is inescapable for all people of color. That certainly has been true for me. Despite mainstream education, lifelong citizenship, and doing my part to contribute to our society, I have never stopped experiencing racial inequities—large and small, overt and subtle.

As a young person in the late 1960s in Albany, GA, I badly needed braces—my front teeth were rather protuberant. The town's only orthodontist refused to accept me as a patient. After many calls over several months by my father, a compromise was reached: The orthodontist would treat me with braces, but I would have to secretly come to his office, entering through a back alley door in the evening, after hours. For two years, my mother and I did just that.

Over the years since, the frequency and range of continued big and small injustices might surprise many. Being angrily called the N-word as a child reading a *Popular Science* magazine at a newsstand; having an apartment landlord slam the door in my face just minutes after he confirmed by phone the availability of multiple units to rent; having a famous cardiologist at a major hospital question why I needed to know where the MRI room was, since it had just been cleaned. In this last example, I had arrived after hours to install the first cardiac imaging software in that MRI system—software that I had developed, written, and would later teach to this same cardiologist. I will never forget a referring physician describing his Black patient to me in disparaging racial terms over the phone, not knowing that I too was Black, and the many times—some in recent years—that I have been approached by policemen in airports to be asked how much money I was carrying or to describe my reason for travel. I was effectively being asked to "show my papers" that would establish my legitimacy.

A version of this personal essay was posted in *Texas A&M Today* (July 20) and published online in *AAMC Insights* (July 24).

These episodes don't kill you in 8 minutes and 46 seconds, but they are deadly. They can kill spirit, a sense of humanity, and any sense of equity. They prevent a sense of belonging. They stifle creativity, realization of potential, and contributions to solving big problems like a cure for Alzheimer's, a vaccine against a deadly virus, or sustaining a clean climate. They remove any sense of societal fair play or meaningful opportunity. The peaceful protesters, who are racially, ethnically, and generationally mixed and global, realize this systemic ill. They realize that through our connectedness, this ill is injurious to us all. It is a blight on our planet.

So how do we get out of this? How do we realize the change for which so many from varied demographic sectors throughout the world are now calling? I think the answer lies, in substantial part, in a communal experience that teaches us we comprise one beautiful human mosaic.

When people learn that our shared humanity binds us one to the other, that differences which do not involve character actually bring character to our interwoven lives, that is when our society will honor its stated commitment to life, liberty, and the pursuit of happiness for all.

This reflection is dedicated to the memory of
US Congressman John Lewis (1940–2020).

Roderic Pettigrew and Rep. John Lewis at the 2016 Candle in the Dark Awards Gala of Morehouse College. Rep. Lewis received the Candle Award for achievements in civil rights and public service. Dr. Pettigrew is a previous award recipient.

Guest Editors' Note

The Role of Nuclear Energy


Jacopo Buongiorno


Michael Corradini


John Parsons


David Petti

This issue of *The Bridge* comes at a pivotal moment of transformation of the global energy system. The desire to reduce the carbon intensity of human activities and strengthen the resilience of infrastructure key to economic prosperity and geopolitical stability shines a new spotlight on the value and challenges of nuclear energy. Critical questions in the areas of nuclear economics, new market potential, advanced reactor technologies, and nuclear regulations are explored in seven original papers authored by distinguished scholars.

We are grateful to the authors for their contributions, to Ashley Finan for writing the Foreword, and to *Bridge* managing editor Cameron Fletcher for assistance throughout the process of inviting and evaluating the papers. We also appreciate thoughtful input from the following who assessed the drafts for accuracy, coverage, and substantiation: **George Apostolakis**, Steven Aumeier, **Robert Budnitz**, Bob Coward, Mike Ford, Céline Kermisch, **Kathy McCarthy**, Mike Middleton, **Pete Miller, Fred Moody**, Greg Nemet, **Per Peterson**, Staffan Qvist, Jovica Riznic, and Robert Rosner.

Jacopo Buongiorno is a professor of nuclear science and engineering at the Massachusetts Institute of Technology (MIT). Michael Corradini (NAE) is Wisconsin Distinguished Professor Emeritus, College of Engineering at the University of Wisconsin–Madison. John Parsons is a senior lecturer in the Sloan School of Management at MIT. David Petti is director of the Nuclear Fuels and Materials Division at Idaho National Laboratory.

Foreword

Nuclear Energy: Context and Outlook

Ashley Finan is director of the National Reactor Innovation Center at Idaho National Laboratory.

Humankind faces significant challenges in energy, the environment, and security. Efforts to leave future generations a world that is safer, cleaner, and more prosperous must determine now how to provide energy while reducing contributions to and mitigating the effects of climate change.

Climate Change and Energy

Globally, fossil fuels account for 63 percent of electricity generation and 84 percent of primary energy consumption (BP 2020), negatively impacting human health and safety. In 2016 household and ambient air pollution together accounted for approximately 7 million deaths, or about 13 percent of mortality, around the world (WHO 2020). Yet the use of fossil fuels is growing, even as 13 percent of the global population—nearly 1 billion people—have no access to electricity (World Bank 2020).

Fossil fuels also contribute substantially to climate change (USGCRP 2018), which is likely associated with risks of increasingly intense storms as well as drought, wildfires, and rising sea levels (Emanuel 2007; Hsiang et al. 2014). In addition, a 2018 World Bank report projects that, on the current path of global warming, over 143 million people around the world could be compelled to migrate within their countries by 2050 (Rigaud et al. 2018). And in 2018 the US government's *Fourth National Climate Assessment* estimated that climate change could cost this country hundreds of billions of dollars annually by the end of the century (USGCRP 2018).

Fortunately, there is growing interest in a decarbonized energy system, and awareness is expanding to people who make policy and technology decisions in the United States and throughout the world. The International Energy Agency (IEA 2020) reports generally accelerating growth in government investments in energy research and development, particularly in low-carbon energy, over the past several years.

The IEA contends that, by investing deliberately in energy innovation, countries have an opportunity to "stimulate economic recovery and help reshape the energy system to be more sustainable and resilient in the longer term" (Gül et al. 2020). And in its Sustainable Development Scenario,[1] the IEA found that technologies currently at the stage of large prototype or demonstration account for about 35 percent of needed cumulative emission reductions (Gül et al. 2020).

These findings and circumstances underscore the importance of broadly investing in advanced energy R&D, in particular the potential role of nuclear as a cost-effective, reliable component of an integrated low-carbon energy system that includes a diverse set of renewable and clean technologies.

In This Issue

The articles in this issue address advances, opportunities, and needs in nuclear energy as well as its role in current and future decarbonization efforts. They highlight research, development, and demonstration tasks pivotal to ensuring that nuclear technology can contribute meaningfully to addressing global energy challenges. They also highlight safety, resilience, and flexibility attributes of advanced nuclear energy systems, and lay out some of the regulatory and investment challenges that must be overcome.

Bruce Hallbert and Kenneth Thomas set the stage by explaining the value of sustaining and extending the operation of the current nuclear fleet based on carbon avoidance and economic impact. They describe various research activities of the US DOE Light Water Reactor

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[1] https://www.iea.org/reports/world-energy-model/sustainable-development-scenario

Sustainability (LWRS) program in predicting and addressing materials degradation, supporting the implementation of digital instrumentation and controls, and evaluating and demonstrating advanced applications of nuclear energy, such as hydrogen production.

Karen Dawson, **Michael Corradini,** John Parsons, and David Petti highlight results from modeling efforts showing the roles of firm, fast-burst, and fuel-saving electricity generation technologies in a decarbonized electricity system. In cost-optimized low-carbon modeling scenarios, nuclear energy deployment generally expands, especially as nuclear energy costs fall.

Charles Forsberg and Shannon Bragg-Sitton demonstrate the importance of addressing electricity and heat consumption to reduce greenhouse gas emissions. The high capital and reduced operating costs of key low-carbon energy technologies favor baseload operation, which the authors suggest could be enabled by the ability to switch production among electricity, heat, and hydrogen. Integrated energy systems would offer this flexibility and optimization.

Eric Ingersoll, Kirsty Gogan, and Giorgio Locatelli contrast capital costs for nuclear power plants built in Asia and those constructed in the United States and Europe, and review cost drivers that explain the differences. They itemize ways that standardized designs, manufacturing approaches, advanced technologies, and project management and execution practices can deliver competitive nuclear capital costs.

Jessica Lovering and Jameson McBride illustrate the trade-off between economies of scale and learning effects by calculating hypothetical break-even deployment points for small and very small reactors. They also suggest policy levers that would enable and encourage learning effects.

José Reyes, Finis Southworth, and Brian Woods describe advanced safety characteristics in next-generation reactors, highlighting the value of those features in enhancing resilience, flexibility, and functionality for new applications.

Richard Meserve reviews regulatory challenges that must be addressed to enable efficient licensing of advanced reactors—existing regulations do not neatly apply to the new technologies and designs. Training, testing, and licensing changes are needed in areas as diverse as fuels, siting, containment, and safety systems.

Conclusion

Together, these articles present a strong case for the valuable role of nuclear energy in decarbonization and offer proposed solutions to challenges. They catalogue some of the progress that has been made with existing technology while focusing on the promise and possibility of nuclear energy and its advanced applications. The overarching message is that nuclear is a critical and reliable component, complementing other low-emission resources, of the nation's sustainable energy network.

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Improved plant efficiencies and reduced operating costs are imperative to sustain the existing fleet of light water reactors.

Sustaining the Value of the US Nuclear Power Fleet

Bruce P. Hallbert

Kenneth Thomas

Bruce P. Hallbert and
Kenneth D. Thomas

Sustaining the value of the US nuclear power fleet can be achieved through cost-effective, reliable operation to deliver diversity, robustness, environmental benefits, and national leadership. Many owners plan to operate nuclear plants for 60 years and more to capture this value. Doing so requires ensuring the integrity of key materials and the economic viability of these plants in current and future energy markets.

Introduction

The fleet of US commercial nuclear power reactors has 96 operating plants (NRC 2019), many of them in their first period of extended operation (i.e., 40 years or more). Two sites have received approval for license renewal (from 60 to 80 years); another 6 plants have applied and 13 have announced similar intentions.

The fleet's sustained operation can be achieved through continued reliable operation; effective maintenance and monitoring of vital structures, systems, and components (SSCs); and viable economics in current and future energy markets.

Bruce Hallbert is national technical director of the DOE-sponsored Light Water Reactor Sustainability Program and Kenneth Thomas is a senior research staff member, both at Idaho National Laboratory.

The Value of Continued Operations

Sustained operation of the US nuclear fleet provides needed and irreplaceable value through fuel source diversity, energy reliability, environmental sustainability, synergy with renewable forms of electricity, economic value, and vital national capabilities and leadership with nuclear power technologies.

In 2019 US nuclear reactors achieved a capacity factor of 93 percent, delivering over 800 million MWh to US residential consumers and industry—and avoiding 476 million metric tons of carbon emissions compared to fossil energy sources.[1] Nuclear energy supplies nearly 20 percent of US baseload electricity and 55 percent of US non-carbon-emitting electricity,[2] and can reliably supply energy when intermittent renewable sources (e.g., wind, solar) cannot. This is especially important in regions where intermittent sources are expected to increase their contributions to domestic electricity capacity (EIA 2019).

Communities surrounding nuclear plants benefit greatly. The Nuclear Energy Institute (NEI 2015) found that a typical nuclear plant generates approximately $470 million in sales of goods and services and almost $40 million in direct high-paying jobs annually. Tax revenue, reported to be about $67 million per site, supports local public schools, roads, and other infrastructure (NEI 2015). The Brattle Group estimates that the commercial nuclear industry accounts for 475,000 jobs and contributes $60 billion annually to US gross domestic product (Berkman and Murphy 2015).

Conversely, reports show that premature closures of commercial nuclear plants depress economic activity in the surrounding area (Stewart et al. 2014) and lead to higher electricity prices (Potomac Economics 2015), greater carbon emissions (Abel 2016; Content 2014), and substantial reductions in municipal operating budgets that depend on tax revenues from an operating nuclear plant (NEI 2017).

Keys to Sustainability

Sustaining the value and contribution of nuclear power to the nation's energy mix involves addressing a number of challenges. Since more than half of existing plants are in their first period of extended operation it is vital to ensure that they can continue to perform needed functions. With several utilities planning to operate their nuclear plants beyond 60 years, additional information is needed to ensure the dependability of existing materials to function over longer service periods (Busby et al. 2014).

Premature closures of commercial nuclear plants lead to higher electricity prices and greater carbon emissions.

The nuclear power industry also faces economic challenges to continued operation. The move in many states to deregulated electricity markets (Warwick 2000, rev 2002) and the recent availability of inexpensive natural gas and influx of subsidized renewable energy (i.e., wind and solar) mean that some nuclear plants are operating in areas where the market price of electricity is below their production costs. The actual and announced shuttering of several operating nuclear plants has ensued, with more at risk. Improved plant efficiencies and reduced operating costs are imperative to sustain the existing fleet of light water reactors (LWRs).

Solutions for Continued Safe and Economic Operations

In 2007 the US Department of Energy (DOE), with the Electric Power Research Institute (EPRI) and other industry stakeholders, initiated planning that led to creation of the Light Water Reactor Sustainability (LWRS) Program (INL 2007). Since then, the DOE, EPRI, and US Nuclear Regulatory Commission (NRC), through memoranda of understanding, have been collaborating with nuclear industry stakeholders to support the continued safe and economic operation of US nuclear plants. The LWRS Program serves as the DOE Office of Nuclear Energy's lead in these collaborative efforts and conducts research and development on materials, plant modernization, flexible plant operation and generation, risk-informed systems analysis, and physical security.

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[1] Nuclear Energy Institute, US Nuclear Generating Statistics, 1971–2019, https://www.nei.org/resources/statistics/us-nuclear-generating-statistics

[2] US Energy Information Administration, What is US electricity generation by energy source?, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3

In the following sections we consider the need for dependable materials, cost-effective operation (including through modernization, diversified revenue, and risk-informed approaches), and physical security.

Dependable Materials

Research by the LWRS Program aims to enhance understanding and prediction of long-term environmental degradation and behavior of materials in nuclear power plants and to provide methods to assess and monitor SSC performance. Materials research focuses on reactor metals, concrete, cables, and potential mitigation strategies (i.e., repair and replacement). Collectively, the following research activities are developing techniques and methods to address damage that occurs during the extended service life of reactor metals and other materials, and to offer candidate replacement materials when such repairs are needed.

Metals

Aging of reactor pressure vessel (RPV) steels results in radiation-induced hardening, manifested as increases in the ductile-brittle fracture temperature (ΔT) for the remainder of a plant's service life. A primary objective of the LWRS Program's research is to develop a robust physical model to accurately predict transition temperatures at high fluence (at least 10^{20} neutrons/cm^2, with energy $E > 1$ MeV) for vessel-relevant fluxes pertinent to extended plant operations.

> *Understanding the role of alloy composition, flux, and total fluence is important because current regulatory models may underpredict steel hardening at high fluence levels.*

Understanding the role of alloy composition, flux, and total fluence is important because current regulatory models (e.g., both the Eason-Odette-Nanstad-Yamamoto model and the new American Society for Testing and Materials E900 Standard) may underpredict hardening in steels at high fluence levels.

In 2018 the LWRS Program completed development of an updated model for ΔT at high fluence. The improved predictive models of RPV steel embrittlement were used to develop a multiphysics model, named Grizzly (Spencer et al. 2018), a simulation tool that accounts for aging effects on material properties and the overall thermomechanical response of the RPV to loading.

Concrete

The properties of concrete in a radiation field change over time because of ongoing changes in the microstructure driven by radiation conditions (spectra, flux, fluence), temperature, moisture content, and loading conditions. Research is being conducted to improve understanding of chemistry and radiation-induced degradation mechanisms and the levels of irradiation that the concrete structures may experience when the reactor life exceeds 60 years.

The Microstructure-Oriented Scientific Analysis of Irradiated Concrete (MOSAIC) software tool was developed to assess the susceptibility of plant-specific concrete to radiation-induced structural degradation (Giorla 2017). The MOSAIC tool incorporates the response of concrete and its components to temperature, moisture, constraint, radiation, creep, and composition variations.

Efforts are continuing to develop a method for use in establishing risk-informed guidelines to evaluate the performance of aging safety-related concrete SSCs.

Cables

Cable-aging research aims to increase understanding of the mechanisms that result in changes to cable performance and to enable more accurate assessments of these changes for use in managing in-service materials during extended operations. Investigators seek to characterize the interaction of environmental and material properties on the performance of cables and to develop improved nondestructive examination (NDE) techniques of in situ cable materials.

The goals of this research are to produce a predictive model of cable aging and degradation and to deliver NDE methods that can be qualified to ensure cable integrity through industry cable-aging management programs.

FIGURE 1 *Left:* Characteristic instrumentation in a nuclear power plant control room is dominated by analog technology. *Right:* Palo Verde operators participate in a control room modernization workshop in the Human Systems Simulation Laboratory at Idaho National Laboratory. Reprinted with permission from LWRS (2020).

Mitigation Strategies

Potential mitigation techniques include weld repair, postirradiation annealing, water-chemistry modifications, and replacement options for the use of new materials with reduced susceptibility to various modes of degradation.

Cost-Effective Operation

A number of nuclear plants are undertaking efforts to improve their long-term competitive positions to address the challenges of operating in a price point–dominated market. These include initiatives to reduce operating costs through greater efficiencies in plant operation and to diversify and increase sources of revenue. The LWRS Program and others are working with owner-operators to spearhead efforts that will be viable for others in the industry.

Creating Efficiencies Through Modernization

Since most plants were constructed years ago, their instrumentation and human-machine interfaces rely on analog technologies, such as those shown in figure 1. Replacing them is broadly perceived as involving significant technical and regulatory uncertainty, which may translate into project delays and substantially higher costs for these refurbishments.

LWRS Program research addresses critical gaps in technology development and deployment to reduce risks and costs and support deployment of new digital instrumentation and control technologies. Rather than merely replacing aging technologies with more modern technologies that perform exactly the same functions, digital approaches—and associated strategies, technical bases, and cost justifications—are being developed to transition to more technology-centric (i.e., automated) and less labor-centric (i.e., manual) plant operation. These modernizations both enable significant operating cost reductions and improve human-system and overall plant performance.

Plants are participating in R&D activities in which new technologies are developed and validated for use (figure 1). Vendors, suppliers, and owner-operators are similarly contributing to efforts to reduce costs through automated system performance monitoring. The Technology-Enabled Risk-Informed Maintenance Strategy (TERMS) draws on their input to integrate advances in online automated asset monitoring, data analysis techniques, and risk assessment methods to reduce maintenance costs (Agarwal 2018). TERMS is also developing technology to enhance the reliability of plant systems, lower maintenance costs, reduce downtime, and increase power generation—and revenue—by increasing plant availability.

Diversifying Revenue

Opportunities may exist in the near future for nuclear power plants to revolutionize their operating paradigm and diversify their revenue by dispatching either thermal or electrical energy to produce nonelectrical products. The LWRS Program is collaborating with plants to

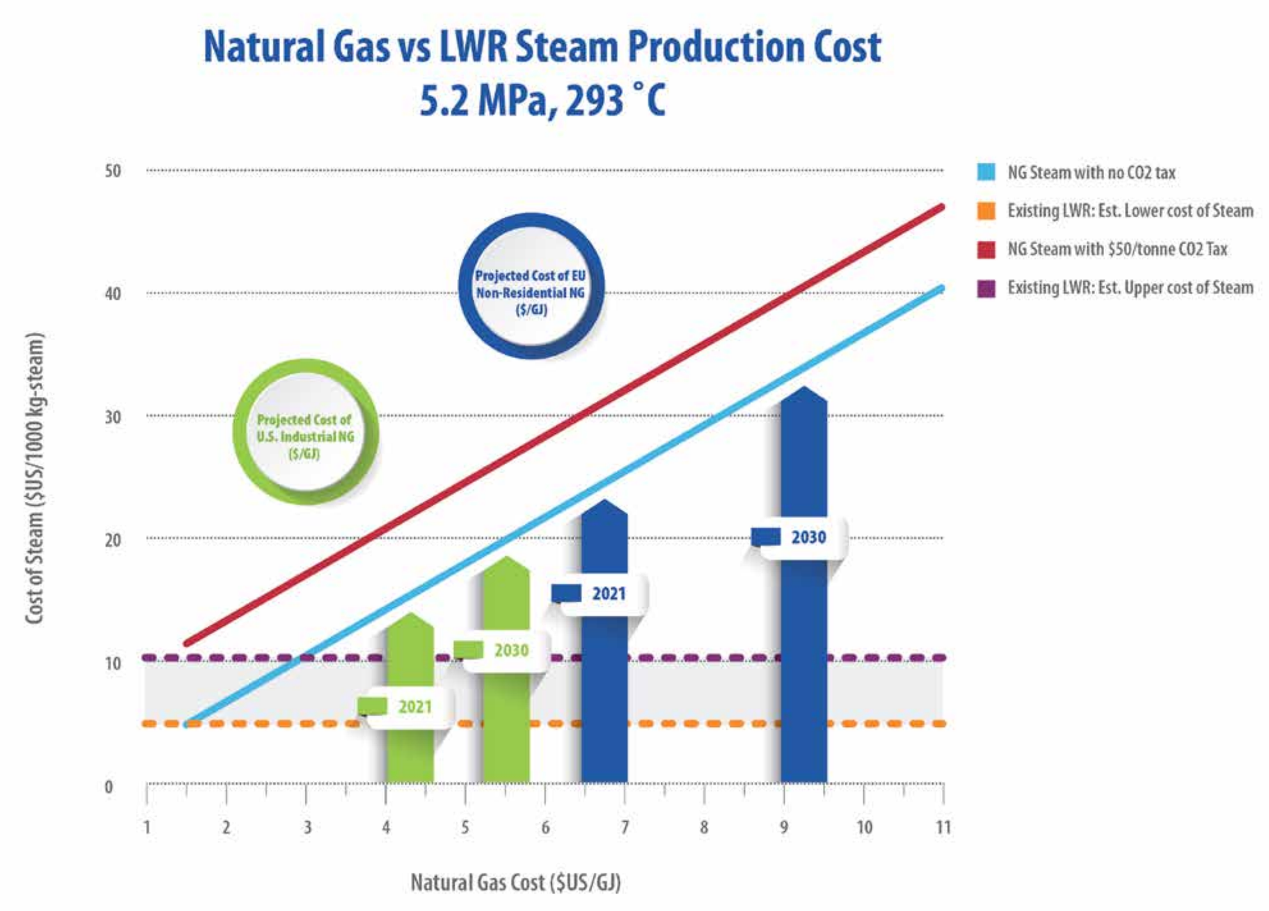

FIGURE 2 Projected cost of high-pressure steam production using natural gas (NG) and nuclear energy in the United States and European Union, 2021–30. Arrows indicate US Energy Information Agency cost projections for natural gas. GJ = gigajoule; LWR = light water nuclear reactor.

explore the technical feasibility and economic viability of such a game-changing development by investigating and evaluating technologies and markets near specific nuclear plants that could directly supply energy to industrial users.

The cost of producing high-pressure steam for industrial use is estimated to be $4.00–$5.25 per 1000 lb of steam ($5.25–$11.00 per 1000 kg of steam), depending on plant type and operating costs as shown in figure 2. This is 15–45 percent lower than the cost of producing steam using a natural gas package boiler *before* any credits for CO_2 emissions reduction are applied.

Because demand is increasing for low-carbon-emission products, hydrogen is being considered because it is a clean fuel, is used in a variety of materials manufacturing and chemicals production, and can be used for trucks and cars that run on hydrogen-powered fuel cells.

A design and evaluation study that coupled either a low-temperature electrolysis plant or a high-temperature steam electrolysis plant to a nuclear plant identified two business opportunities for LWR-supported electrolysis: (1) smaller plants would produce hydrogen for fuel-cell vehicle filling stations where low-temperature electrolysis plants can be competitive with natural gas steam reforming plants; (2) at industrial plants that use a large amount of hydrogen, steam electrolysis was shown to be competitive with large-scale natural gas steam reforming plants (Boardman et al. 2019).

Recent DOE awards demonstrate movement toward a future in which nuclear plants devote more of their operations to produce hydrogen or other products. These projects emphasize low-temperature electrolysis using polymer electrolyte membrane cells, but options are being considered for other hydrogen production systems.

The LWRS Program also completed an independent evaluation of the production of fertilizers, steel, and synthetic fuels using hydrogen produced by LWRs and CO_2 from ethanol plants.

Using Risk-Informed Approaches to Reduce Costs

Since the transition in the late 1980s to greater use of risk-informed approaches to safety assessment and management, there has been a gradual openness to use them in many aspects of nuclear plant operation and maintenance. This shift may support greater flexibility in managing plant operations within established safety margins.

LWRS collaborations with owner-operators, EPRI, and others are investigating improvements in resilience for nuclear power plants, cost and risk categorization applications, and margin recovery and operating cost reduction. Each involves the development of advanced analytical methods and tools, tested in collaborative projects to ensure that the results can be used by other owner-operators.

One project is exploring how advanced technologies may enhance the resilience of LWRs (Ma et al. 2019). The study is considering accident-tolerant fuel, industry investments in diverse and flexible coping strategies implemented as a result of post-Fukushima enhancements, and passive cooling technologies for improved decay heat removal. The performance of these measures is being analyzed by new tools that integrate probabilistic risk assessment and thermal hydraulic analysis to demonstrate benefits for plant operation and safety. Collectively these may improve economics by offering the potential to recategorize some safety-related SSCs as nonsafety and reduce operating costs.

Physical Security

Implementation of enhanced physical security requirements to protect against an attack at US nuclear power plants after September 11, 2001, resulted in larger onsite physical security forces and costs that are comparatively high relative to other operational costs. LWRS Program research to improve efficiencies and optimize costs to ensure physical security at commercial plants includes risk-informed approaches to physical security.

Current industry practices in plant physical security assessments use "target sets" and security modeling tools to analyze the timelines and effectiveness of a given security posture (i.e., physical security elements and the typical means for their use) against a defined adversary. The integration of analyses of physical protection with plant system responses enables modeling of the timeline from the start of an attack to radiological and other consequences of concern. The LWRS Program is studying ways to achieve this integration to improve the technical basis for stakeholders' decisions so that they both optimize physical security and realize operation and maintenance cost benefits.

Summary

The LWRS Program and collaborating organizations conduct research, development, and technology demonstrations to achieve progress in key areas needed for the continued operation of nuclear power plants. These activities and their accomplishments directly support the mission of the LWRS Program on behalf of the DOE Office of Nuclear Energy: to develop science-based methods and tools for the reliable and economical long-term operation of the nation's high-performing fleet of commercial nuclear power plants.

> *Integration of analyses of physical protection with plant system responses enables modeling of the radiological and other consequences of an attack.*

Nuclear power has reliably and safely supplied approximately 20 percent of electrical generation in the United States over the past two decades. It remains the country's single largest producer of non-greenhouse-gas-emitting electricity, supports the resilience of the electricity grid at a time of increasing growth in intermittent energy sources, and is transitioning to generate other needed nonelectric products. It provides value to the national economy and local communities through numerous direct benefits.

Sustaining the operation and value of the existing US nuclear fleet is a national imperative requiring the efforts of a broad cross section of stakeholders such as the DOE, NRC, EPRI, owner-operators, vendors, and suppliers to the commercial nuclear power industry.

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Our analysis shows the potential contribution of nuclear as a firm low-carbon technology.

The Case for Nuclear as a Low-Carbon, Firm, Widely Available Energy Source

Karen Dawson, Michael Corradini, John Parsons, and Jacopo Buongiorno


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Deep decarbonization of economies will require thoroughgoing changes to all parts of the energy system, including replacing a large share of fossil fuel consumption with low-carbon sources. What will be nuclear's place in this transformation?

Options for Decarbonized Energy

Nuclear power is the largest source of low-carbon energy in the United States and Europe, and the second largest source worldwide after hydropower. In the past, nuclear was primarily chosen as a baseload technology, evaluated

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in comparison against other baseload options such as coal- or natural gas–fired technologies. But will these be its competitors in a deeply decarbonized system?

Wind and Solar

The fastest-growing sources of low-carbon generation worldwide are wind and solar photovoltaic (PV) technologies. Over the years 2018–50, the US Energy Information Administration's reference case scenario shows these technologies growing at average annual rates of 4.9 percent and 7.2 percent worldwide, respectively, while the growth rate for nuclear is approximately 1 percent (EIA 2019).

Nuclear power is the largest source of low-carbon energy in the United States and Europe.

The expanding grid penetration of renewables is changing the competitive landscape. But the variability of wind and solar energy resources injects a new dimension to the problem of choosing a portfolio of investments that reliably matches supply with demand at low cost.

Even the modest penetration of renewables observed so far has forced changes to the operation of national grids to adapt to the high variability of wind and solar resources. Some of this adaptation has been just a matter of time and technical innovation. For example, while earlier vintages of wind and solar installations contributed nothing to frequency regulation or operating reserves, current vintages can, and in some countries network codes are being revised to require this functionality.[1] System operators have also modified their load forecasting to incorporate more detailed information on anticipated wind speeds, significantly improving unit commitment and dispatch decisions.

Unintended Impacts

Some of this adaptation has lagged, creating economic conflict and losses. For example, policymakers in many countries used out-of-market payments (e.g., feed-in tariffs, production tax credits) to incentivize investment in renewables. This approach has depressed electricity wholesale prices—even driving them negative in some hours of the day—with the uneconomic result of pushing a number of legacy nuclear plants to be retired prematurely.

When existing nuclear plants are shut down, their generation is typically replaced by either natural gas and coal or a mix of variable renewables and fossil fuels. As a result, the carbon footprint of the electric grid inevitably increases, as observed following the closure of US nuclear plants (e.g., Crystal River in Florida [2009], Kewaunee in Wisconsin [2013], San Onofre in California [2013], Vermont Yankee in Vermont [2014], and Pilgrim in Massachusetts [2019]).[2]

Policies governing wholesale market design and the electricity sector need to be updated for the new reality of a grid that accommodates both variable renewables and other low-carbon technologies to exploit the contributions of each to the decarbonized grid. New policies should allow existing nuclear plants to continue to operate, avoiding emission increases that set back the gains of other low-carbon sources (as seen for example in California and Germany).

The Capacity Planning Problem

All electricity systems, however organized, must find a solution to the capacity planning problem: What portfolio of technologies and power plants should be built to serve future load? One of the criteria applied is minimization of total system cost,[3] which includes both the up-front investment in capacity and the later expenses of operation, including fuel costs.

Historically, because dispatchable thermal technologies have dominated most systems, portfolio optimization sorted technologies into categories such as baseload, load-following, and peaker (operating only at times of peak demand). The technologies were pri-

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[1] A report prepared for the Australian Energy Market Operator gives a good feel for the evolution in this area (Miller et al. 2017). See also Ela et al. (2014), Varma and Akbari (2019), and Wu et al. (2018).

[2] For documentation of the impact of nuclear plant closures on CO_2 emissions, see Davis and Hausman (2016) re San Onofre, Neidell et al. (2019) re Japan's closures immediately after Fukushima, and Jarvis et al. (2019) re Germany's policy decision to close its nuclear plants.

[3] Cost minimization is a crucial but admittedly narrow focus. The energy mix should be and typically is determined by consideration of broader economic impact (jobs, taxes, business opportunities), local environmental impact (air quality, land use), fuel supply security and diversification, resilience of the energy infrastructure, geopolitical relationships, etc.

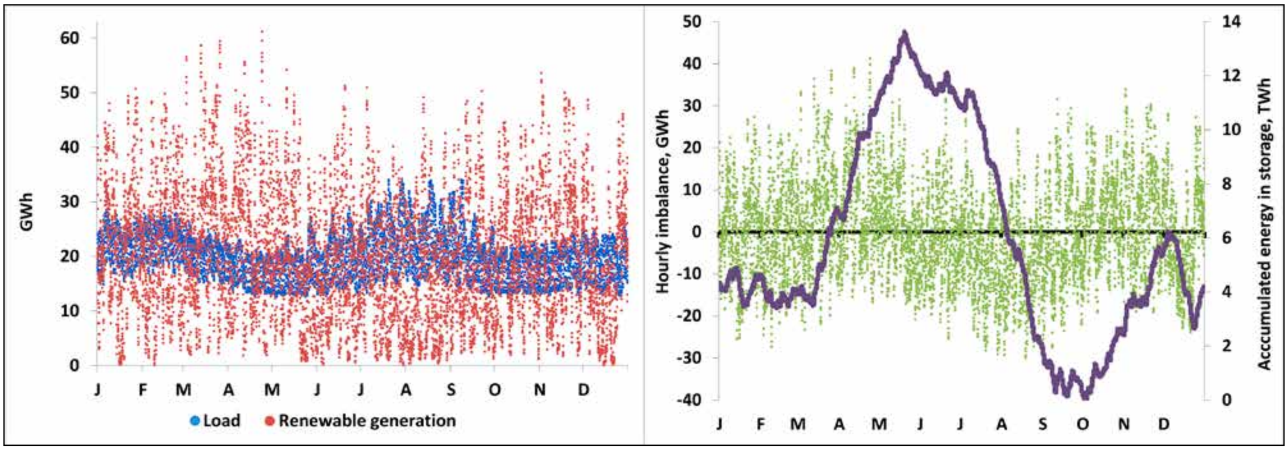

FIGURE 1 Mix of wind and solar photovoltaic capacity scaled to match aggregate annual load, based on New England load and weather data for 2018. *Left:* Hourly electricity load (blue band) and simulated renewable generation (red). *Right:* Simulated total state of storage (purple trendline) and hourly charge and discharge (surplus or deficit; green) of storage system.

marily distinguished by the trade-off between fixed costs (mostly capital costs, but for nuclear also fixed operating costs) and variable costs (primarily fuel).

High fixed cost technologies can yield a low average cost of generation so long as they are operated with a high capacity factor. They are therefore chosen to serve the baseload portion of the load curve. This is the market niche in which nuclear has historically competed.

Low fixed cost, high variable cost technologies can yield a lower average cost of generation when the capacity factor is low, so they are chosen to serve the peak load portion of the load curve. Combustion turbines are an ideal technology for this niche. The optimal mix of technologies is determined by their fixed and variable costs and by the load curve.

Profile of Annual Renewable Resource Availability

The introduction of renewables into the set of available technologies brings in a new factor: the profile of renewable resource availability through the hours of the year, with daily, seasonal, and synoptic variability. Expanding the use of renewables can add a high volume of generation to some hours of the year, but not others.

Figure 1 illustrates the problem. The left side shows the hourly load in the six New England states in 2018; it appears as a dense, gently undulating blue band of hourly data points. The width of the band reflects the daily fluctuation in load: it expands in the summer months, and peaks there, too, with a secondary peak in the winter. The left side also shows, in red, a simulation of renewable generation from a hypothetical portfolio of wind and solar PV facilities. The size of the portfolio is chosen so that total renewable generation for the year equals total load for the year.

For this thought experiment we did not analyze whether it is environmentally sustainable to deploy PV panels, wind turbines, and their associated transmission infrastructure on such a grand scale. The fluctuations in hourly generation reflect the varying insolation and wind across the hours. These are much larger in scale than the fluctuations in load.

Although the simulated renewable generation matches load in the aggregate over the year, within any shorter interval there is a large mismatch. For this portfolio of renewable capacity to successfully serve load, it would have to be complemented with facilities that can store the surplus electricity in some hours and release it back in other hours.

The right side of figure 1 shows in green the hourly charge and discharge (surplus or deficit) of a hypothetical lossless storage system, along with the total state of charge (storage; purple). While the storage is used to smooth the daily fluctuations in generation, the figure makes clear that there is a large seasonal cycle to the storage. The total capacity of the storage system must be nearly 14 TWh, which is enormous.

Alternatives to Storage

One alternative to a seasonal storage system is to enhance wind and solar capacity so that even in the low resource hours there will be sufficient generation to meet load. Doing so would mean that total renewable generation capacity would far exceed total load, and in some hours there would be very large curtailments. Fig-

TABLE 1 Old and new taxonomy of electricity-generating technologies according to their place in a complete portfolio to meet demand, following Sepulveda et al. (2018)

	Old Taxonomy				
Service:	**Baseload**	+	**Load following**	+	**Peaker**
Sample technologies:	Nuclear		Natural gas combined cycle		Combustion turbine
	Coal				
	New Taxonomy				
Service:	**Fuel saving**	+	**Firm**	+	**Fast burst**
Sample technologies:	Solar PV		Nuclear		Battery
	Wind		Reservoir hydro		Demand response
	Run-of-river hydro		Gas w/ CCS		Hydrogen

CCS = carbon capture and sequestration; PV = photovoltaic.

ure 1 shows the limits of this option: there are quite a few hours when the total renewable resource is very low, so that an extremely large amount of capacity would be needed. Another alternative is to invest in extensive long-distance grid connections that diversify the variable generation assets accessible to load.

The most viable alternative is to identify other low-carbon generation technologies for use whenever renewable generation is too low. These include nuclear, reservoir hydro, geothermal, hydrogen, and biofuels. A survey of studies on deep decarbonization pathways identifies this role of "firm" (i.e., reliable) low-carbon resources as critical (Jenkins et al. 2018a).

This is a new way of thinking about constructing an optimal portfolio of generation technologies. It is no longer enough to focus on the load curve. It is now necessary to appreciate the interaction between the time profile of load and resource availability. Expanded investment in renewables adds a high volume of generation to some hours of the year, but not others. While the dramatic drop in costs has made wind and solar PV the economic choice for incremental investment, as penetration expands additional investments fall because these resources are not serving load in the most deficient hours. Other technologies are required to serve these hours or to store energy from low-carbon generation and deliver it to these hours.

Table 1 contrasts the old and new ways of thinking. In the new taxonomy (proposed by Sepulveda et al. 2018), nuclear competes among firm low-carbon resources complementing intermittent renewables. While nuclear has a place in both taxonomies, its place in the portfolio changes.

The Opportunity for Nuclear Energy in a Decarbonized Electricity System

We have examined nuclear's new role in a decarbonized electricity system (Buongiorno et al. 2018). Projecting to 2050, we asked, What are least-cost mixes of generation technologies to serve loads in diverse regions while achieving targeted reductions in carbon intensity? We paid particular attention to how the accelerated growth of variable renewable technologies such as wind and solar PV alters the optimal portfolio mixes.

Explanation of Our Model

We applied a capacity expansion and dispatch model to the conditions in a variety of regions with different load and renewable resource patterns. We chose six regions, two in the United States (New England and Texas), two in China (Tianjin-Beijing-Tangshan and Zhejiang), and two in Europe (France and the United Kingdom). In this paper we focus on the US regions.

We used the GenX model, a constrained optimization model that determines the least-cost mix of investments required to serve electricity demand in a future planning year (Jenkins and Sepulveda 2017). The optimization criterion is total system cost, which includes the capital expenditures to install the capacity as well as the subsequent operating expenditures.

The model assumes that capacity is dispatched and operated to minimize the total system cost, subject to constraints. The constraints include the requirement that net generation equal load in each of the 8760 hours of a representative year, taking into account the availability of storage and demand response.

Hourly renewable generation is constrained by installed capacity and by the hourly availability of the renewable resource. Generation units must operate within their technical constraints, such as minimum load, maximum ramping capacity, and so on. For example, we assume that nuclear plants have a minimum generation level of 50 percent and can ramp at a rate of 25 percent per hour, while gas turbines have a minimum generation level of 24 percent and can ramp at 100 percent per hour.[4]

Finally, aggregate CO_2 emissions must be within a specified constraint. GenX can be configured for different levels of detail. For example, it can incorporate opportunities for demand response as well as certain defined transmission constraints; the study discussed here did not include the former and treated each region as if it had no transmission constraints and no trade outside the region. GenX can also be parameterized to include existing capacity and to choose new investments, but the study discussed here focused on a greenfield mix for 2050—i.e., with no inherited capacity. The exception is hydro facilities, which were fixed at the existing level.

The model requires inputs on the available technologies, their operating constraints, and capital and operating costs. The technologies included were utility-scale solar PV, on-shore wind, large-scale traditional nuclear reactors, natural gas with carbon capture and sequestration (CCS), coal with CCS, open-cycle gas turbine, combined-cycle gas turbine, coal, pumped-hydro storage, and battery storage. This is a limited set of technology options, but its range is broad in terms of key characteristics.

Technologies compete among each other in important ways. The options included in the analysis and the cost inputs chosen shape the results. The full report details a number of scenario analyses performed to expand on the basic results.

Total System Cost

A portfolio optimization that looks at total system cost is essential, and far superior to comparisons of levelized cost of electricity (LCOE) numbers for competing technologies. While LCOEs can be useful summary benchmarks of the different cost inputs, comparing LCOEs across technologies implicitly assumes the technologies compete head-to-head to serve similar loads. As explained above, in reality, technologies are often best suited to serve certain portions of the load and ill suited to serve others, so that what may seem to be competing technologies are actually complementary. Our implementation of GenX addresses this issue and brings out both the opportunity for nuclear and the challenge of cost.

TABLE 2 Emission intensity of the electricity sector, 2014 actual versus 2050 scenario goal

	2014	2050
World	540	35
United States	486	11
China	698	24
Europe	350	1

Source: IEA (2017), Energy Technology Perspectives, 2°C Scenario.

Details on the cost assumptions are available in the MIT study report (Buongiorno et al. 2018), but some key figures are useful to mention here. The nominal or base case assumption for the overnight capital cost of nuclear in the two US regions for 2050 is \$5500/kW in 2014 dollars (we also considered a case in which the capital cost for nuclear is decreased by 25 percent to \$4100/kW; the study contains a number of sensitivity analyses on various parameters). A concise summary of these inputs is the LCOE of key technologies.

Assuming the nuclear plant operates at a 90 percent capacity factor, the LCOE is just over \$100/MWh. In contrast, assuming capacity factors for wind and solar of 34 percent and 25 percent, respectively, and approximating the available resource factors across our US regions, the LCOEs for wind and solar are \$72/MWh and \$52/MWh. So nuclear is an expensive alternative. Yet it may be a valuable part of a portfolio because of its capability to generate during hours when the renewable technologies are less available.

We calculated the optimal portfolio in each region under different assumptions about the level of decarbonization as measured by the carbon intensity of the system, starting at 500 gCO_2/kWh and falling to 100, 50, 10, and finally 1 gCO_2/kWh.[5] To benchmark these different levels, table 2 contrasts the recent historical

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[4] Contrary to popular belief, the output of many large nuclear power plants in Europe and the US is routinely adjusted according to system requirements. Many provide frequency regulation service, others operate in a load-following mode at daily and weekly scales, and some adjust to seasonal needs. See EPRI (2014), Jenkins et al. (2018b), Keppler and Cometto (2012), and Ponciroli et al. (2017).

[5] Our modeling measures and constrains only direct emissions. All technologies have so-called indirect emissions attributable to the infrastructure and the supply chain. The direct emissions from fossil fuels are outsized relative to the indirect emissions from most technologies and so have been the focus of policymakers. Moreover, if a policy addressing direct emissions is broad enough, encompassing most sectors, then the indirect emissions from one sector will be captured as direct emissions in another. Eventually, as large sources of direct emissions decline, the relative variation in indirect emissions will gain attention.

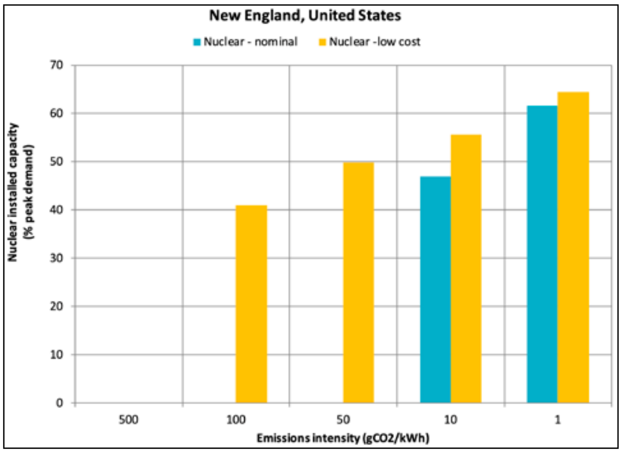

FIGURE 2 Hypothetical nuclear installed capacity in New England based on economic optimization to meet CO_2 reduction targets. Nominal case cost for nuclear = $5500/kW in 2014 dollars (blue bars), low cost for nuclear = $4100/kW (yellow bars).

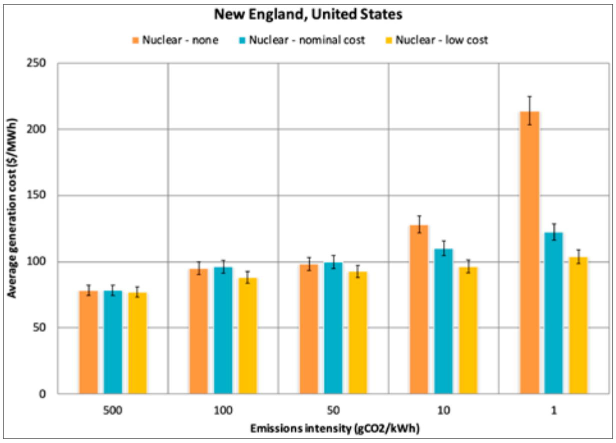

FIGURE 3 Average system cost of electricity in New England for various decarbonization targets and across three scenarios for nuclear: nuclear excluded (orange bars), nominal cost for nuclear = $5500/kW in 2014 dollars (blue bars), low cost for nuclear = $4100/kW (yellow bars).

level of carbon intensity of the electricity sector with the 2050 goal established for a scenario developed by the International Energy Agency (IEA 2017) to be consistent with a 2°C target for global warming. For example, the 2014 US level was 486 gCO_2/kWh, while the 2050 goal is 11. For China it was 698 gCO_2/kWh in 2014, and 24 in 2050.

Figure 2 shows optimal builds of new nuclear capacity in New England depending on the level of decarbonization targeted and the assumed cost of a plant. The blue bars show the results for the nominal case assumptions. Given the high cost assumed for nuclear and the quality of renewable resources in New England, significant emission reductions are accomplished without nuclear: both the 100 and 50 gCO_2/kWh carbon intensity targets can be theoretically achieved at lowest cost without any nuclear capacity. However, deep decarbonization brings nuclear into the optimal mix.

Figure 2 shows that (i) for deep decarbonization (emission intensity levels of 10 to 1 gCO_2/kWh) nuclear is an important element of the portfolio that minimizes system cost and (ii) lowering the cost of nuclear makes a dramatic difference to the scale of nuclear—although it is a potentially valuable player in a decarbonized grid, cost is a determining factor for its scale. The MIT report includes a number of scenario analyses with varying cost assumptions, including about the cost of alternative firm, low-carbon technologies; naturally, nuclear's role in the cost-minimizing portfolio varies with these assumptions.

While figure 2 emphasizes the impact of lower cost on nuclear's role in a portfolio, the reverse is also true: if nuclear projects in the United States and Europe continue to have cost overruns (as recent projects have), then nuclear will not play an important role in a cost- or carbon-minimizing portfolio.

Figure 3 reports the average generation cost at each decarbonization target and for different assumptions about nuclear. In all cases, costs increase as the target for carbon intensity becomes tighter. The orange bars show the impact on costs of excluding nuclear from the mix. The figure makes clear that excluding nuclear is very expensive in terms of climate change mitigation, and its inclusion is comparable with other energy options.

The GenX analysis shows that the use of nuclear energy in regions and nations is regionally dependent, which one would assume given the variability of solar and wind as well as the costs to deploy the technologies.

Conclusion

Meeting the world's energy needs while simultaneously reducing greenhouse gas emissions is an enormous challenge. Meeting this challenge in the electricity sector will require a new mix of generation assets. While a variety of low- or zero-carbon technologies can be used in various combinations, our analysis shows the potential contribution of nuclear as a firm low-carbon technology.

It is time to transform thinking about energy production. Renewable and nuclear energies are complementary, not mutually exclusive. Existing nuclear power plants should be preserved and new ones designed and delivered.

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The roles of nuclear, wind, and solar energy depend on three factors: heat vs. work, capital cost, and transport.

Maximizing Clean Energy Use:

Integrating Nuclear and Renewable Technologies to Support Variable Electricity, Heat, and Hydrogen Demands

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Shannon Bragg-Sitton

Charles W. Forsberg and Shannon M. Bragg-Sitton

Fossil fuels are hard to beat: low cost, easy to store, and easy to transport. They enable the economic provision of variable electricity and heat to the customer because the capital cost of power plants, furnaces, and boilers is small relative to the cost of the fuel. It is economic to operate fossil plants at part load—the money is in the fuel.

But concerns about environmental emission of carbon dioxide (CO_2) may limit the continued use of fossil fuels. To reduce CO_2 emissions, the primary energy options to meet electricity and heat demand are nuclear, wind, solar, hydro, and fossil fuel generators with carbon capture and sequestration (CCS). These energy sources have relatively high capital costs and relatively low operating costs. Operating high-capital-cost technologies at reduced load significantly increases the average cost of energy. Furthermore, no combination of these resources matches the variable demand for heat and electricity unless they are periodically operated at reduced capacity in a "load following" mode.

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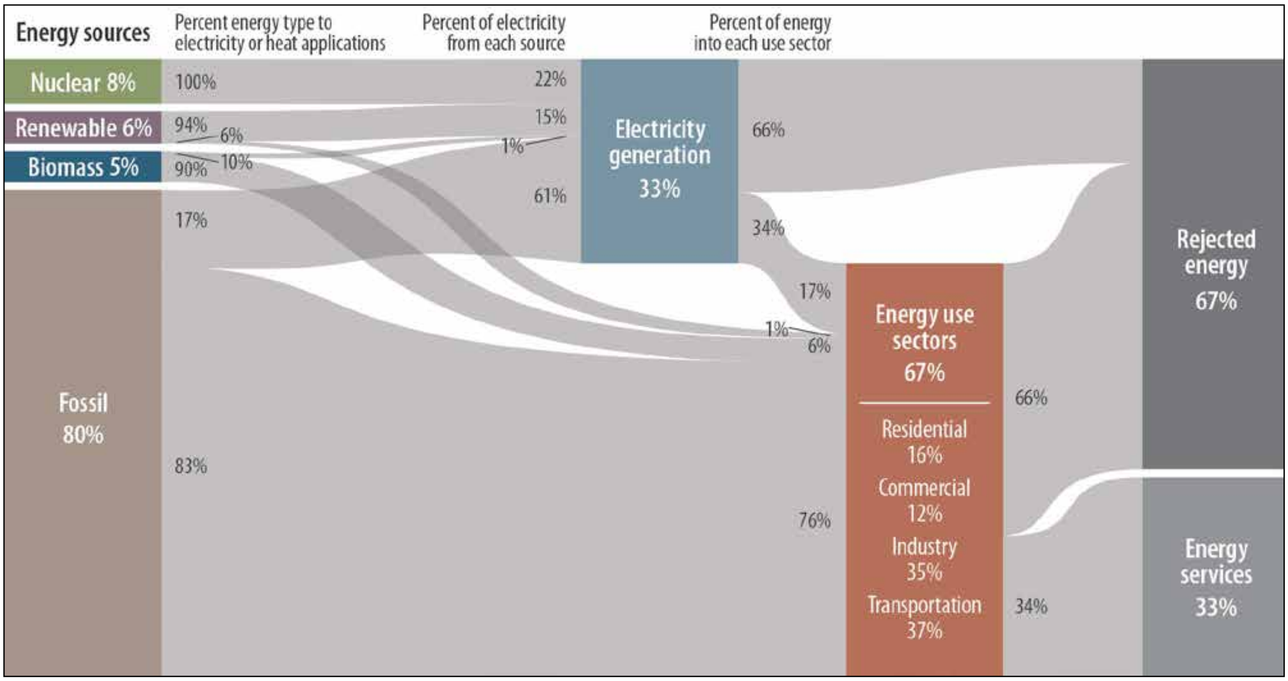

FIGURE 1 2018 Energy sources and energy consumers in the United States. "Fossil" comprises natural gas, coal, and petroleum. "Renewable" comprises wind, solar, and hydro. Note that across all "Energy use sectors" only 17% of energy use is electricity, with the remaining 83% in the form of heat. Adapted from LLNL (2020).

The question addressed in this paper is how to leverage multiple energy sources to meet variable energy demands at the lowest cost to the consumer while simultaneously reducing CO_2 emissions and meeting stringent requirements for reliability and resilience.

Production of Heat and Electricity

The starting point is to consider what the customer needs. Figure 1 shows energy sources (left column) and uses (brown column) in the United States adapted from a Sankey diagram (LLNL 2020) where (i) wind, solar, and hydro have been combined into a single renewable energy input and (ii) natural gas, coal, and petroleum are combined to create the fossil energy input. Fossil fuels are 80 percent and renewables 6 percent of the energy input. About half the renewable input is from hydro resources, and all of it is dependent on the weather.

Most energy is consumed in the form of heat—what fossil fuels provide. The heat demand across all energy sectors far exceeds electricity use—83 percent versus 17 percent of the energy use sector demand. In the industrial sector, 88 percent of the energy use is heat (LLNL 2020). The transport sector uses heat for internal combustion engines and jet engines. The commercial and residential sectors use approximately equal amounts of heat and electricity.

In total energy consumption across all generating technologies, the data in figure 1 reveal that two-thirds of generated energy is rejected while only one-third supports energy services (far right column). In the electricity sector the rejected heat is from the conversion of heat to electricity as a result of thermodynamic and engineering limits of heat engines.

Nuclear energy, like that of fossil-fueled generators, is dispatchable, meaning that energy is available when it is needed—on demand. Wind and solar output are dependent on local wind and solar conditions; hydroelectricity is either variable (run-of-the-river hydro) or dispatchable (dam). However, of equal importance is that nuclear reactors produce heat (the primary energy product used by society), whereas hydro, wind, and solar photovoltaic (PV) produce electricity.

The laws of thermodynamics dictate that several units of heat are required to produce a unit of electricity. Typical light water reactors (LWRs) have a heat-to-electricity efficiency of 33 percent, so the cost of heat is roughly a third that of electricity. As a consequence, nuclear energy and other thermal generators, such as fossil fuels, produce low-cost heat and more expensive

TABLE 1 Levelized cost of electricity (LCOE) and heat (LCOH). Based on Lazard (2018). PV = photovoltaic.

Technology	Primary output	LCOE: \$/MWh(e)	LCOH: \$/MWh(t)	Low-carbon	Dispatchable
Solar PV: rooftop home	Electricity	187–319	187–319	Yes	No
Solar PV: crystal, utility	Electricity	46–53	46–53	Yes	No
Solar PV: thin film utility	Electricity	43–48	43–48	Yes	No
Solar thermal w/ storage	Heat	98–181	33–60	Yes	Yes
Wind	Electricity	30–60	30–60	Yes	No
Natural gas (NG) peaking	Heat	156–210	20–40	No	Yes
NG combined cycle	Heat	42–78	20–40	No	Yes
Nuclear fission	Heat	112–183	37–61	Yes	Yes

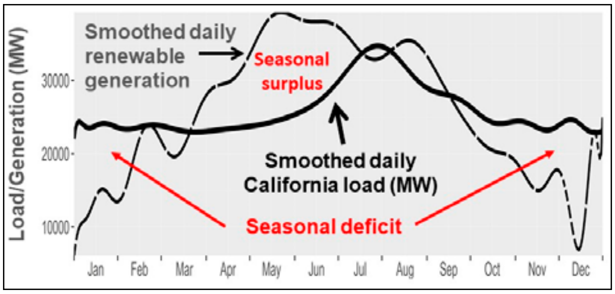

FIGURE 2 Smoothed California electricity demand and renewable generation with total annual renewable generation equal to total annual electric demand. Courtesy of S. Brick, California Case Study, Clean Air Task Force.

electricity. Direct electricity sources (hydro, wind, and PV) produce heat via resistance heating, resulting in higher-cost heat. More efficient electricity-to-heat technologies such as electrically driven heat pumps have proven viable only near room temperature.

Table 1 reports the levelized cost of electricity (LCOE) and heat (LCOH). Most industrial customers want constant heat input, while other customers have relatively uniform electricity demands when averaged over several days with the exception of heating and cooling demands. The outputs of wind and solar do not match constant demand because they vary on a daily to seasonal basis.

Figure 2 shows the smoothed wind and solar production and electricity demand in California over one year (where smoothing averages the higher-frequency daily and weekly variations). To provide significant electricity and/or heat, wind and solar technologies would need to include the additional cost of energy storage to match production to demand.

Finally, the cost of transmission and delivery (NEA 2019) must be included, approximately doubling the cost of electricity to the consumer relative to the production cost. Hence, use of grid electricity to support thermal energy demands is about six times the cost of natural gas–derived heat.

The large cost differences between heat and electricity have significant implications. The industrial superpowers of the 21st century will likely be those countries that successfully integrate industrial heat demand with nuclear energy or fossil fuels with CCS. Large heat consumers could be supported by nuclear reactors. Smaller industrial facilities, however, may shift to industrial parks in which heat is provided by common nuclear or fossil systems with CCS. Only some locations are suitable for CO_2 sequestration. Thus, low-carbon futures without nuclear energy imply industry movement to locations with low-cost natural gas and CO_2 sequestration sites (e.g., Texas).

Recent studies indicate large differences in the capital cost of nuclear power with location: low costs in China, South Korea, and Japan and much higher costs in western countries (Buongiorno et al. 2018; Gogan et al. 2018). Capital cost differences primarily reflect the differences between serial production in Asian countries versus low rates of nuclear plant construction in western countries where each new plant essentially is a first-of-a-kind plant. For western countries to remain industrial powers in a low-carbon world, a secure nuclear power supply chain is a priority to lower energy costs. A low-carbon world also favors deployment of high-temperature reactors (e.g., high-temperature gas-cooled reactors [NGNP 2011] and salt-cooled reactors [Forsberg 2020]) that can meet a larger fraction of industrial heat demand and can operate at higher thermal-to-electric efficiencies.

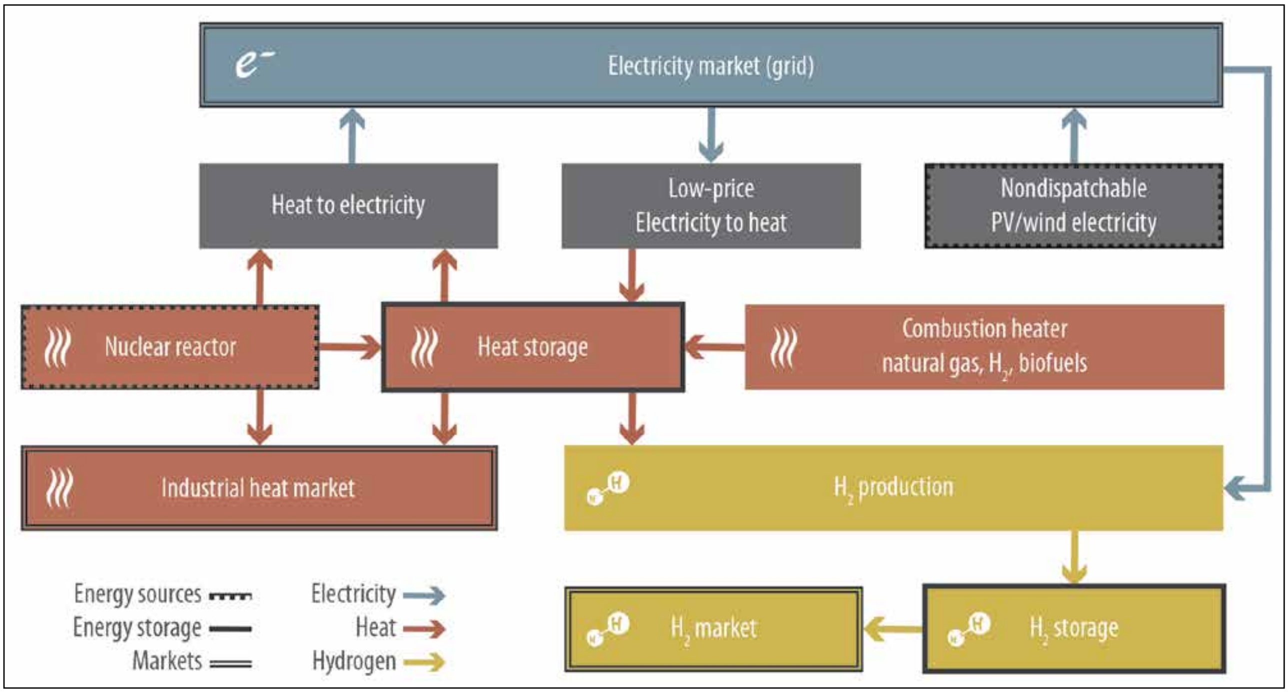

FIGURE 3 Baseload nuclear, wind, and solar with heat storage to provide variable heat, electricity, and hydrogen. PV = photovoltaic.

Integrating Energy Sources with Heat Storage

Modeling studies of low-carbon electricity grids (Sepulveda et al. 2018) show that the lowest-cost systems are some mixture of dispatchable (nuclear and fossil with CCS) and nondispatchable (wind and solar PV) systems. These models include electricity storage and methods of demand management.

If an electrical system primarily comprised wind and solar PV, it would typically double the cost of electricity because of the high costs of overbuilding renewable capacity and associated electricity storage systems required to meet demand. Similarly, the high capital cost of nuclear reactors creates incentives for steady-state operation that may not match the demand for heat and electricity. The question is then how to create a low-cost energy storage system that enables efficient use of nuclear and renewable technologies.

There are three primary options for large-scale storage media:

- electricity storage (e.g., pumped hydroelectric facilities and batteries),
- heat storage, and
- chemical storage (e.g., hydrogen and its derivatives, such as ammonia) that can be stored in tanks or geological formations.

Heat storage couples to heat-generating technologies (e.g., nuclear), whereas electricity storage technologies couple to wind, solar PV, and the grid.

A system design that incorporates nuclear-coupled heat storage while supporting peak demand is shown in figure 3. The nuclear reactor operates at baseload to minimize the cost of energy production with heat output that can go in several directions: upward to the power conversion block that converts heat to electricity, downward to the industrial heat market, and to the right into heat storage. Solar PV and wind produce electricity that goes to the grid.

The central box, heat storage, can receive heat from several sources. Most of the heat comes from the nuclear reactor at times of low demand for electricity and industrial heat. If there is low-price electricity, grid electricity can be converted into stored heat using resistance heaters coupled to the heat storage system.[1] Last, if heat storage is depleted, a combustion heater can produce heat as needed by burning natural gas or low-carbon hydrogen/biofuels.

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[1] From a thermodynamic perspective, converting high-quality electricity into heat is inefficient. However, from an economic perspective it is better than curtailing electricity production from systems with low operating costs.

The stored heat can be used for three purposes: it can be converted to electricity at times of high demand—adding to the electricity from the nuclear reactor heat-to-electricity power cycle, wind, and PV; it can be sent to industrial or commercial customers; or it can be used for hydrogen production (discussed later). Heat storage makes it possible to balance production with demand while the relatively high-capital-cost nuclear, wind, and solar facilities operate near full capacity—their most economic operating mode.

> *Storage enables industrial systems to optimize heat consumption in a way that maximizes electricity, product revenue, and decarbonization.*

Cogeneration of electricity and heat directly links the industrial heat market to electricity markets. Coupling the industrial sector with the electricity sector via storage adds a new dimension to balancing production with demand. Unlike traditional cogeneration where one must match production with demand on a second-by-second basis, the requirement is to match production with demand over a period of several days. Many industrial processes have the capability to vary their heat input over a period of hours or days but not over short periods of time. Storage enables industrial systems to optimize heat consumption in a way that maximizes electricity and product revenue, in parallel with decarbonization of the industry and electricity sectors.

Heat Storage Technologies

There are many heat storage technologies that could couple to nuclear reactors (Forsberg 2019; Forsberg et al. 2019). Many were first developed for concentrated solar power (CSP) systems. The largest CSP storage systems store heat in liquid nitrate salts where the temperature varies from 285°C to 565°C. Cold nitrate salts enter the CSP system, are heated, and are then sent to the hot-salt storage tank, such that there is no efficiency penalty in charging the storage system—unlike what is experienced for pumped hydro or battery storage. Hot nitrate salt is sent to steam generators where water is converted into steam to drive the power cycle. The resulting cold salt is sent to the cold-salt storage tank and ultimately back to the CSP system to be reheated.

Multiple hot and cold nitrate salt storage tanks are in use, capable of storing several gigawatt hours (GWh) of heat, with typical dimensions of 40 meters in diameter and 12 meters high. If such heat storage systems are coupled to high-temperature reactors, the nitrate salt loop that incorporates storage replaces the intermediate heat transfer loop that separates the reactor from the power cycle. As in CSP plants, there is no efficiency loss in adding heat storage to such a system—only slow small losses through insulated storage system components, as would be inherent to any thermal system (although insulation minimizes losses due to heat transit through the component and piping walls, it is not possible to fully eliminate heat loss).

Other CSP systems use heat transfer oils with operating temperatures below 400°C. These heat storage systems are compatible with existing LWRs with peak temperatures of ~300°C.

Today CSP plants store hot and cold nitrate salt or oil in large tanks. Second-generation systems (under development) fill the storage tanks with crushed rock or other lower-cost fill materials to provide lower-cost heat capacity and thereby reduce the required quantities of nitrate salts (Odenthal et al. 2019) or oils (Amuda and Field 2020; Kluba and Field 2019) in the tanks.

Proposed third-generation systems for heat storage capacities up to 100 GWh (Forsberg 2020) store heat in crushed rock in insulated trenches up to 60 meters wide, 20 meters high, and a kilometer long with insulated roofs. Hot oil or hot salt from the reactor is sprayed over and heats sections of crushed rock as it flows down to the collection pan under the crushed rock. The oil or salt is then cycled back to the reactor to be reheated. At times of high electricity demand, cold oil or salt is sprayed on the hot rock, flows through the rock to the collection pan, and is sent to the power block or industrial customer.[2]

The US Department of Energy goal for the capital cost of heat storage systems is $15/kWh of heat. Commercial nitrate salt storage systems cost ~$20/kWh (Forsberg et al. 2019), with the goal to reduce capital

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[2] Heat storage systems using latent or thermochemical heat are under development, but most of this work is in the research phase (Barnes and Levine 2011).

costs by an order of magnitude with third-generation systems (Forsberg 2020). Current commercial heat storage system costs per unit of electricity are a factor of 3 to 4 less than electricity storage technologies, reflecting lower-cost materials of construction (i.e., crushed rock and thermal salts versus lithium, cobalt, or steel). The cost difference reflects the fundamental difference between storing heat versus work (electricity). The largest deployed energy storage technology today is hydro pumped storage; however, the cost and availability of this technology is strongly dependent on location.

Advanced heat storage technologies may be economic for periods of a week or more, but not for seasonal heat storage. Geothermal heat storage (Forsberg 2012) enables seasonal storage. In a geothermal storage system hot water or steam is used to heat rock ~1000 meters underground. This technology depends on appropriate geology and is in the early stages of development.

Hydrogen Systems: The Other Energy Carrier

The United States consumes 10 million tons of hydrogen per year to produce liquid fuels, chemicals, and fertilizer. The hydrogen market could reach 18 percent of energy consumption by 2050 (Miller et al. 2020).

In a low-carbon world hydrogen is a chemical reagent in the production of fertilizer, metals, and biofuels; for example, it replaces fossil fuels as a chemical reducing agent in the production of steel (Millner et al. 2017) and other materials. Future markets may include hydrogen use in fuel cells for vehicle transport and hydrogen combustion as a high-temperature heat source for industry (e.g., for cement production), although in these markets there are competitive alternatives.

There are two primary hydrogen production options: reforming and water splitting. Steam methane reforming (SMR) of fossil fuels (where inclusion of CCS, currently not used, would reduce carbon emissions) is the predominant method of hydrogen production. Hydrogen is in a chemically reduced form as a component of methane (CH_4), whereas for water-splitting processes it is in its oxidized form—water (H_2O).

In SMR, natural gas and steam are converted to hydrogen and CO_2, taking less energy than electrolytic processes. In a low-carbon world, SMR is expected to be the economic option in locations with low natural gas prices and good carbon sequestration sites.

Water splitting for hydrogen production is accomplished via low-temperature electrolysis of water using electricity, high-temperature electrolysis (HTE) of steam, or thermochemical hydrogen production from water with heat input. These processes are less technically mature than SMR (Dinh et al. 2017). However, HTE has an economic advantage because part of the energy input is in the form of steam that costs less than electricity, no expensive catalyst is required, and the process is more efficient in converting water to hydrogen and oxygen. While one cannot predict technological futures, the expectation is that HTE will become the low-cost electrolytic route.

Hydrogen production facilities are capital intensive with large economies of scale. Because it is uneconomic to operate them at low capacity factors, they may need to operate more than 80 percent of the time (Boardman et al. 2019).

Seasonal mismatch in energy production and demand can be partly addressed by nuclear-renewable-hydrogen production systems.

Figure 3 shows a hydrogen plant embedded in a system that includes nuclear and renewable generators and heat storage. At times of low electricity prices, electricity from the grid can be used for HTE while lower-value heat from the nuclear plant is directed to storage and the HTE unit. At times of high electricity prices, heat from the reactor and heat storage produce peak electricity with no hydrogen production. This system has several characteristics:

- *Hydrogen storage*. Large-scale hydrogen storage, on an hourly to seasonal basis, is inexpensive through use of the same underground storage facilities used for natural gas. Hence, stopping hydrogen production does not disrupt the hydrogen supply to the customer.
- *Electricity sink*. The system design allows wind and solar electricity at times of low prices to produce, with nuclear heat, higher-value hydrogen while excess heat from the nuclear plant is directed to lower-cost heat storage. Capital-intensive nuclear, wind, solar, and hydrogen facilities are all operated at high capacity factors.

- *Seasonal mismatch.* Seasonal mismatch between generation and demand (figure 2) can be partly addressed by nuclear-renewable-hydrogen production systems where the nuclear plant produces hydrogen most of the year but can be redirected to provide electricity when needed.

Nuclear-driven hydrogen production facilities show technical and economic potential in some US markets (Boardman et al. 2019; Frick et al. 2019), and US utilities are working to demonstrate these technologies at existing LWR power plants (Dillon and Klump 2019; Wald 2019).

Conclusions

There has been less than a decade of work to understand how to deploy a low-carbon energy system. Work is underway to develop integrated system approaches (Bragg-Sitton et al. 2020a,b). While the details depend on technology developments, three factors will drive system design and the roles of nuclear, wind, and solar:

- *Heat versus work.* Nuclear reactors produce heat that couples to low-cost heat storage technologies, whereas wind and solar PV produce electricity that couples to higher-cost electricity storage technologies. This implies different roles in a low-carbon energy system. Low-carbon fossil fuel systems with CCS generate heat and thus play the same role as nuclear in this system.

- *Capital cost.* All low-carbon energy production systems have relatively high capital costs and low operating costs. Operating these systems at low capacity factors results in expensive energy. Low-cost storage (heat and hydrogen) may enable these energy production technologies to operate at high capacity factors to minimize energy production costs.

- *Energy transport.* Fossil fuels are inexpensive to transport, resulting in relatively flat worldwide energy prices. Heat can be transported efficiently over short distances, but suffers significant losses over longer distances. Electricity and hydrogen have high transport costs relative to fossil fuels, but can be efficiently moved over longer distances. Wind and solar are location dependent, while nuclear energy systems can be deployed almost anywhere. These differences imply a future low-carbon energy world with large differences in energy production methods as a function of location, as well as large geographical differences in energy costs.

The fundamental characteristics of different energy generation and storage technologies cannot be changed by technological advances. Given the goals to minimize CO_2 emissions and energy costs, those characteristics will drive energy system design for a low-carbon world no matter which specific nuclear, wind, or solar technologies, or which mix of them, are ultimately used.

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The US nuclear sector needs to shift to standardized products with replicable designs delivered by consistent, experienced suppliers.

Managing Drivers of Cost in the Construction of Nuclear Plants

Eric Ingersoll, Kirsty Gogan, and Giorgio Locatelli


Eric Ingersoll


Kirsty Gogan


Giorgio Locatelli

To make a meaningful contribution toward clean, reliable, and economical future energy systems, nuclear power plants (NPPs) must be cost and risk competitive with other low-carbon technologies within near-term timeframes. Recent new builds in the United States and western Europe have suffered from two phenomena. First, they are expensive in absolute and relative terms: the cost per MW installed, along with the size of the plant, makes them among the most expensive power plants of any type. Second, they have all been delivered overbudget and late, making NPP construction a risky investment, which in turn increases the cost of borrowing money for new projects.

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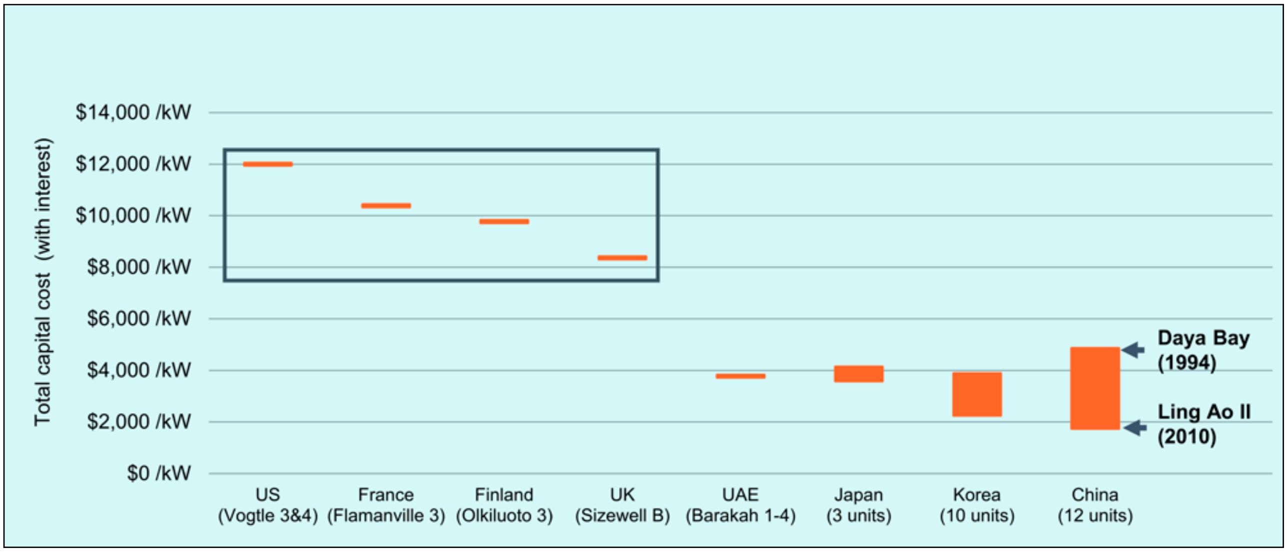

FIGURE 1 Total capital costs for historical and ongoing nuclear projects in eight countries. Costs comprise those for base construction plus contingency, interest during construction, owner's cost (including utility startup), commissioning (nonutility startup), and initial fuel core. Reprinted from ETI (2018).

But the experience in Asia has been very different. Many new build projects there are highly cost competitive with both fossil fuels and renewables. Figure 1 highlights this contrast, plotting the costs for a sample of representative projects, four in the United States and European Union, and a number of projects in four Asian countries.

Understanding Differences in NPP Capital Costs

Research helps to explain the differences. The Nuclear Cost Drivers Project commissioned by the UK Energy Technologies Institute (ETI NCD study; ETI 2018) reviewed pathways for reducing capital costs, which comprise those for base construction plus contingency, interest during construction, owner's cost (including utility startup), commissioning (nonutility startup), and initial fuel core (adapted from GIF 2007). Through an evidence-based study of historic, contemporary, and future NPPs, the project identified a small number of factors that drive NPP costs and risks and highlighted characteristics common among low-cost NPP projects and others common to high-cost projects.

Figure 2 contrasts the elements of capital cost across four groups of NPP projects: (i) a high-cost (first-of-a-kind) group based on current experience in Europe and the United States, (ii) a benchmark plant ("previous US median"), (iii) best-performing US plants, and (iv) low-cost plants based on current experience in the rest of the world (ROW).[1]

The first thing to notice is that despite wide variation in EU/US and Asian labor costs, this category is not the largest contributor to differences in cost outcomes. Second, the green bars show considerable differences in interest during construction, primarily reflecting the duration of construction and capital costs (interest during construction was levelized at 7 percent for all cases here)—projects that experience severe delays cost more. Third, indirect services costs (dark blue) also show substantial variation; they are driven by (in)efficiencies in design completion and the need to resolve quality and regulatory issues, which often entail extensive engagements with regulators and suppliers, additional design engineering work, onsite rework, and delays.[2]

The small sample of highest-cost NPPs shown here are first-of-a-kind (FOAK) projects being built in Europe and the United States after decades of inactivity in construction. In contrast, the majority of those at the low-cost end of the scale are nth-of-a-kind units.

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[1] The ETI NCD study analyzed a range of current and recent projects against a "benchmark plant" representing the median experience from the US fleet build recorded in DOE (1986).

[2] Indirect services costs comprise field indirect costs, construction supervision, commissioning and startup costs, demonstration test run, design services off- and onsite, project/construction management services off- and onsite, and contingency on indirect services cost (ETI 2018).

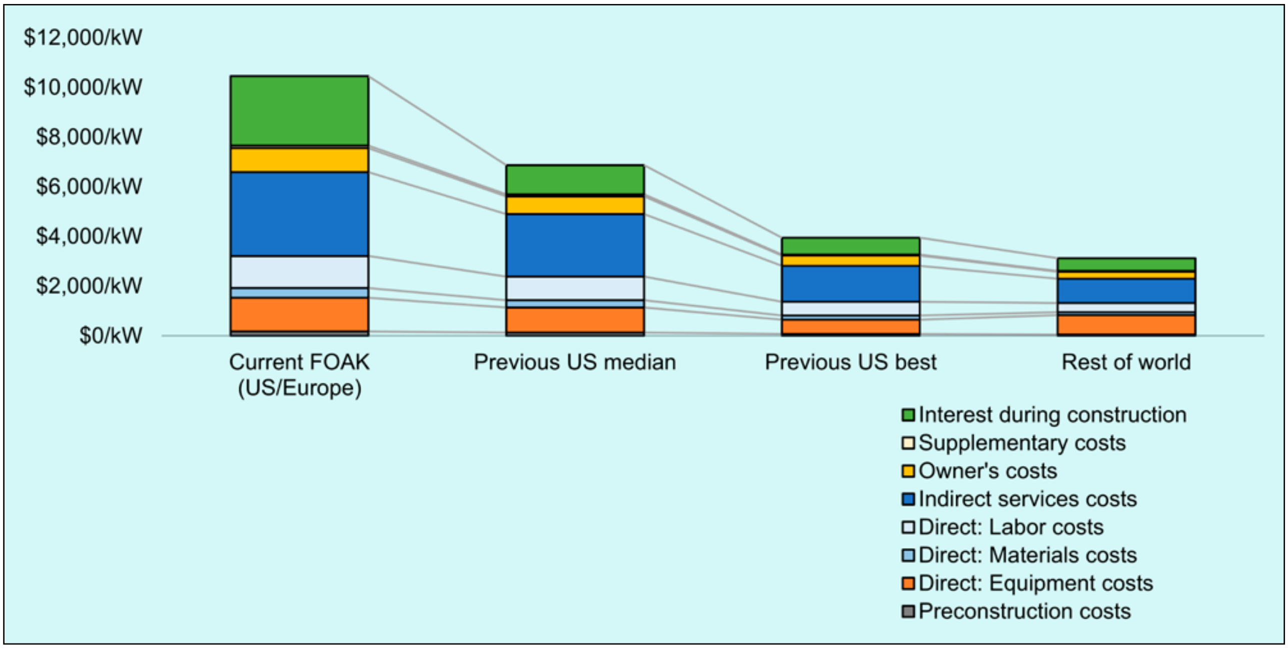

FIGURE 2 Differences between high- and low-cost nuclear plant projects (in 2017 USD). FOAK = first of a kind. Adapted from ETI (2018).

Evidence from NPP new build programs around the world indicates that FOAK plants represent a major investment in skills and capability. Significant productivity improvements and cost effectiveness can be gained in subsequent projects with respect to the project governance, workforce, supply chain, and regulators, in general illustrating the role of experienced leadership, design standardization, and mature capability in reducing costs, delays, and risks (Mignacca and Locatelli 2020).

Ways to Reduce New Build Costs

Of course, cost improvements are not automatic. A review of learning rates with different technologies showed that they vary according to the technology, time of the study, location, and other factors (Rubin et al. 2015). The nuclear industry has had among the lowest learning rates. The lack of standardization in design and the project delivery chain is a key reason for this poor performance.

Once again, however, there is contrasting experience. South Korea has demonstrated a fleet build approach combined with good project management, efficient construction execution, and technology innovation to deliver new NPPs domestically and even in newcomer countries (e.g., the United Arab Emirates) at significantly lower costs than those recently experienced in Europe and the United States (Choi et al. 2009).

It is reasonable to ask whether low-cost outcomes in China, Japan, and Korea, for example, are transferable to the US or European contexts, given cultural and economic differences and country-specific working practices. Evidence gathered in the ETI NCD study suggests that best practices leading to these low-cost outcomes are not country- or even technology-specific. In fact, as highlighted above, analysis reveals that previous US best practice experience (expressed in 2017 USD, and with a standard interest rate during construction of 7 percent applied across all units) corresponds reasonably with current ROW experience, as shown in figure 2 (DOE 1986, table 5-4).

Several studies have identified factors that are key to determining the cost and risk of NPP new build projects (e.g., Buongiorno et al. 2018; ETI 2018). Table 1 reports the main cost drivers and corresponding stakeholders for a new NPP construction project, along with actions that can reduce the impact of each cost driver.

A highly focused, deliberate program can drive down costs and improve efficiency of the construction process over time through consistent, rational implemen-

TABLE 1 Summary of cost drivers, stakeholders, and actions to reduce costs for a new nuclear power plant (NPP)

Cost driver	Action owner	Cost driver description	Actions for cost reduction
Plant design	Developer	All preconstruction efforts related to plant design, including design decisions, design completion, and ability to leverage past project designs; plant-specific details such as capacity, thermal efficiency, and seismic design, as well as broader aspects related to constructability and project planning processes	• Complete design before starting construction • Design for constructability (see Jergeas and Van der Put 2001) • Prioritize increased modularity in the design to shorten and derisk the critical path • Ensure that plant design team is multidisciplinary and has current construction expertise • Design for plant design reuse • Replicate design to minimize redesign • Consider specific design improvements against full costs and potential benefits of implementation
Equipment and materials	Developer	Quantities of equipment, concrete, and steel (both nuclear and nonnuclear grade) used in the plant as well as strategies used to address materials cost	• Reduce quantity of nuclear-grade components as much as possible • Substitute concrete with structural steel where possible • Develop opportunities to use emerging technologies used in other sectors (e.g., high-energy-density welding of thick sections, laser cladding) • Reduce overordering/waste of materials via (digital) production management
Construction execution	Developer	All decisions, practices, and support tools used in engineering, procurement, construction (EPC) during project delivery, from site planning, preparation, and design rework through all onsite decisions (e.g., project execution strategies, interaction with subcontractors and suppliers) to commercial operation date. Includes independent inspection processes, quality assurance and control, and other major cost and risk centers during project construction. This driver is a measure of efficiency and productivity across the entire delivery consortium. For multiunit construction on the same site, this should get better with each subsequent unit.	• Hire effective and experienced managers • Engage an integrated project delivery team operating as a long-term enterprise with aligned incentives • Leverage more offsite fabrication and onsite prefabrication • Ensure that systems/processes are in place for the transfer of people and expertise between projects • Establish a digitally enabled production management system (workflow and coordination) linked to a digital twin and managed by an integrator
Workforce	Developer	All direct and indirect construction labor performed on the project site as well as labor related to offsite manufacturing or assembly; covers productivity, wages, training and prep costs, percentage of skilled workers with direct applicable experience, etc. This driver measures efficiency and productivity at the individual level.	• Innovate methods for developing alignment with labor around NPP projects • Improve labor productivity by increasing training and using the same people across multiple projects • Invest in the labor force with training that emphasizes quality

continued

TABLE 1 Continued

Cost driver	Action owner	Cost driver description	Actions for cost reduction
Project governance/ development	Developer	All factors related to developing, contracting, financing, and operating the project by the project owner; covers topics from the interdisciplinary expertise of the owner's team to number of units ordered (at the same site), discretionary design changes, weighted average cost of capital, and contracting structures with the EPC	• Ensure that the owner's organization has an experienced, multidisciplinary team • Ensure that the project owner develops multiple units (minimum of 2, but fleet benefits increase with additional units) at a single site with the same project delivery chain • Implement programmatic approach to planning multiple projects, including systems/processes to transfer people/expertise among them • Follow contracting best practices (per ETI 2018) • Procure for a cyberphysical asset (i.e., the plant's digital twin) • Establish long-term cooperative partnership between owner and vendor • Plan at the program level rather than project level • Sequence multiple projects to maintain labor mobilization and consistency in delivery teams and the construction supply chain
Political and regulatory context	Government	Country-specific factors related to regulatory interactions and political support (both legislatively and financially): regulatory experience, pace of interactions, details on the site licensing process, and topics related to the government's role in financing and how well it plays certain roles otherwise reserved for the project customer	• Make government support contingent on systematic application of best practices and cost reduction measures • Help put in place a framework to enable project financing • Design a program to maximize and incentivize learning, including clarity on potential future projects • Work closely with the regulator to deliver on cost-effective safety • Engage the regulator early and agree on a process for resolving licensing issues
Supply chain	Suppliers/ vendors	Factors that characterize supply chain experience, readiness, and cost of nuclear qualification as well as nuclear- and non-nuclear-grade equipment and materials	• Embrace a highly proactive approach to supply chain management and qualification • Develop incentive program for suppliers against a schedule of milestones • Develop long-term agreements to involve suppliers across several projects • Develop reasonable risk management strategies, allocating risks to the most appropriate stakeholders (e.g., owner, developer, supplier)
Operation	Owner	All costs related to NPP operations (e.g., fuel price, staff head count, wages, capacity factor, unplanned outages, etc.)	• Involve commissioning staff and operators in project planning and related construction activities • Develop excellence in plant operations and maintenance through training and benchmarking (e.g., World Association of Nuclear Operators peer review program)

tation of best practices, regardless of location, if there is a strong commitment from the major stakeholders. Literature on the cost of megaprojects, across a variety of sectors besides nuclear, validates these points (e.g., Locatelli 2018; Merrow 2011).

Further Cost-Reducing Options

In addition to the adoption of best practices for project management and execution, new technologies may further reduce cost and risk even for GW-scale conventional light water reactors. Examples include the use of seismic isolation to reduce the need for site-specific design changes, and advanced construction materials such as high-strength reinforcing steel and ultra-high-performance concrete to reduce the installation cost of concrete structures (Buongiorno et al. 2018).

Even more radical cost reductions could come from new delivery models in industries that already deliver large, low-cost, high-quality, and complex machines at the scale of NPPs. Shipyards, aircraft factories, and auto manufacturing plants are good examples.

Learning from these other industries demonstrates that steep, near-term cost reduction is achievable by shifting from traditional "stick-built" construction projects to high-productivity manufacturing environments such as a shipyard or factory. Moving from traditional construction to a highly integrated manufacturing, assembly, and installation process on one site could enable high-quality, repeatable processes, with quality assurance designed into every step. For example, thanks to the standardization of design and suppliers, the aerospace industry achieved over the decades extraordinary cost reduction and safety improvement, making flying safe and convenient.

Conclusion

The nuclear sector in the United States and Europe needs to shift from artisan-crafted projects to standardized repeatable products, with NPP planning based on a few replicable designs delivered by a consistent network of experienced suppliers. It is up to the nuclear sector to shift its mindset and lead this transition.

The nuclear sector must also engage with its many stakeholders to explain why nuclear *products* instead of *projects* can deliver lower costs and other wider societal benefits. This is important to create the societal "pull" in the same way that has made flying safe, convenient, and affordable today.

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With targeted policies and fast learning rates, SMRs could reach cost parity with fossil fuels before 2050.

Chasing Cheap Nuclear: Economic Trade-Offs for Small Modular Reactors


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The costs of first-of-a-kind small modular nuclear power reactors (SMRs) and microreactors (<10 MWe capacity) are expected to be high when compared with those of historical large-scale light water reactors (LWRs). There is widespread uncertainty in the nuclear industry about the cost drivers of small reactors after first-of-a-kind builds. "Learning by doing" could result in substantial cost declines as small reactors are deployed in series, facilitated by rapid factory production. On the other hand, scale inefficiencies in small reactors could keep their unit costs stubbornly higher than large-scale designs. These dynamics suggest a trade-off between learning effects and scaling effects in the cost trajectory of small reactors.

Background

Recent large-scale reactor builds in the United States and Europe have been prohibitively expensive as costs escalated over time. Several utilities in the Americas, Europe, and Asia are considering building small reactors as an alternative to new investment in large reactors.

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SMRs can provide novel services that large designs have not, including off-grid and emergency power supply, and collocated industrial process heat. Additionally, hybrid energy systems could incorporate SMRs with renewables to produce a mix of electricity, heat, and hydrogen to optimize economic performance (Aumeier et al. 2011). If small reactors can achieve consistent learning effects over sustained deployment, unit-cost parity with large designs may be possible.

Because factory-produced commercial nuclear power reactors have never been deployed, there is little understanding of how their cost will evolve. Therefore, estimating potential learning effects is a theoretical exercise.

By combining analysis of scaling and learning effects, we explore theoretical deployment levels where SMRs and microreactors reach unit-cost parity with conventional reactors as a function of starting costs, learning rates, and scaling factors. Using ranges of possible values for each parameter, we illustrate potential pathways for microreactor cost evolution.

This study serves two purposes: first, it establishes realistic boundaries on the cost evolution of SMRs and microreactors to help inform investment policy; second, it provides empirical support for attempts to understand comparative learning and scaling effects in factory-fabricated nuclear reactors. We conclude by suggesting policies to drive learning effects and minimize diseconomies of scale.

Economies of Scale for Nuclear Power Plants

Predictions for the growth of commercial nuclear power in the 1950s were predicated on the expectation that the larger reactors of the future would be more cost-efficient. But such economies of scale were not realized.

Early commercial reactors in the United States had capacities of approximately 250–500 MWe per reactor. In the 1960s the industry began building larger reactors, approaching 1 GWe per reactor, but they were considerably more expensive, contradicting the expectation of economies of scale and contributing to the sharp decline in US nuclear construction.

The literature reports a surprisingly small number of attempts to resolve the disparity between expectation and reality for nuclear scaling economics. One study argued that the cost escalation experienced in the US nuclear power industry was caused by industry overestimation of the scaling effect, which led to an inefficient overincrease in unit size over time (Zimmerman 1982). Another found that increases in reactor size tended to extend construction duration and thus escalate costs (Cantor and Hewlett 1988). More recently, studies have cited increased reactor size and complexity (Koomey and Hultman 2007). In France, “big size syndrome”—the nuclear industry built inefficiently larger and more complex plants as it gained experience with the technology—resulted in both longer lead times and higher costs (Escobar Rangel and Lévêque 2015). In short, much of the literature argues that the larger nuclear designs were too complex to be built cost-effectively.

Scaling Relations

Scaling relations are used to predict the cost of scaled-up or scaled-down versions of equipment and processes. For commercial nuclear, scaling relations can connect the empirical costs of large reactors with expected costs of smaller reactors, assuming they are of similar technology.

If small reactors can achieve consistent learning effects, unit-cost parity with large designs may be possible.

In an attempt to quantify the trade-offs between economies of scale and other economies for SMRs, the International Atomic Energy Agency (IAEA 2013) proposes a scaling relation to predict the first-of-a-kind (FOAK) cost for an SMR, given by the following equation:

$$Cost_{SMR} = Cost_{NPP} \times \left(\frac{SMR\ MWe}{NPP\ MWe} \right)^{n-1}$$

where $Cost_{SMR}$ is the overnight capital cost (OCC) of the SMR per unit of capacity, $Cost_{NPP}$ is the OCC of a large-scale nuclear power plant (NPP) per unit of capacity, MWe is the rated power capacity of each, and n is the scaling factor. The IAEA scaling relation applied to reactors of similar designs, so we group reactors in our dataset into fleets of similar designs. The applicability of the empirical scaling factors to a future small reactor design will depend on its similarity to existing technology.

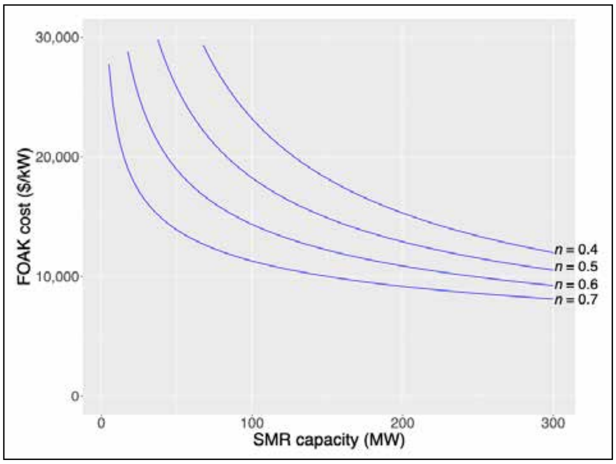

FIGURE 1 Illustration of IAEA (2013) scaling relation for a base plant with overnight capital cost of $5500/kW and capacity of 1100 MW. The blue lines show first-of-a-kind (FOAK) cost for a small modular reactor (SMR) as a function of size in MW for four scaling factors. For microreactors (less than 10 MWe), cost becomes quite large.

Multiple studies have attempted to estimate the scaling factor for nuclear plants. A survey of 26 studies of economies of scale in nuclear power found a range from $n = 0.25$ to $n = 1$, the latter indicating no scaling effect (Bowers et al. 1983). Unfortunately, the surveyed studies include nuclear cost data only through 1982 and are largely restricted to US data. Despite these serious limitations, the scaling factors from the 1983 study are still widely used. For example, their use in a 2010 model of potential costs for small and medium modular reactors suggested that higher costs for smaller reactors might be offset by modularization and fabrication strategies (Carelli et al. 2010). The IAEA (2013) 250 MW SMR case study used a median value of $n = 0.6$, and a more recent study (Moore 2016) used the Bowers et al. midpoint value, $n = 0.55$, in scaling down the cost of a 1000 MW reactor to a 10 MW microreactor.

As an illustrative exercise, we apply the IAEA scaling relation (shown in the equation above) to the cost and size of a Westinghouse AP1000 reactor being built in the United States, assuming an OCC of $5500/kW and capacity of 1100 MW. Figure 1 shows the hypothetical FOAK costs for an SMR as a function of capacity (2.5–300 MW, with four scaling curves covering the range of scaling factors considered by IAEA, $n = 0.4$–0.7.

While the scaling relation assumes that the scaled-down technology remains broadly similar, it can be useful to apply such an equation to advanced SMRs and microreactors as a form of benchmarking. But before we can do so, we need to reexamine what is a realistic range for scaling factor n.

Past studies of nuclear costs, scaling, and learning generally had access only to US and French cost data. We use a much larger global dataset of nuclear construction costs across eight countries (Lovering et al. 2016) and group reactors broadly by technological similarity, as summarized in table 1.

To estimate the empirical scaling factors and learning rates in these groups, we construct a multiple linear regression with ordinary least squares. The regression specification is based on a simplified version of models used by Cantor and Hewlett (1988) and Escobar Rangel and Lévêque (2015), among others.

$$\log(OCC_i) = \beta_0 + \beta_{size}\log(Capacity_i) + \beta_{leadtime}\log(Leadtime_i) + \beta_{exp}\log(CountryExp_i) + \beta_{AtSite}(AtSite_i) + \epsilon_i$$

where we define the following variables:

OCC_i: overnight construction cost in 2010 USD per kW
$Capacity_i$: reactor capacity in MWe
$Leadtime_i$: time between construction start and commercial operation
$CountryExp_i$: cumulative installed capacity in MW in country prior to reactor construction start
$AtSite_i$: number of operating reactors at site at construction completion.

We use the equation $n = \beta_{size} + 1$ to derive for each fleet the scaling factor n from the regression coefficient β_{size}.

Although we see a large range of scaling factors from our data (table 1), the IAEA report is clear that the scaling relationship is meant only for very similar designs (i.e., just a scaled-down version of the large reactor). Past studies have drawn primarily on US data and thus primarily on LWR designs; our historical dataset includes designs for gas-cooled and heavy water reactors as well as LWRs. Many SMRs in development—high-temperature gas-cooled reactors, salt-cooled, metal-cooled, and fast—are non-LWRs. Our scaling factors thus give a more robust approximation of boundary conditions on the range of FOAK costs for SMRs and microreactors, relative to past studies restricted to LWR data.

Scaling Applied to Microreactors

Moore (2016) scales down costs from a 1000 MW reactor to a 10 MW microreactor using a factor of $n = 0.55$

TABLE 1 Summary of reactor cost data used in our multifactor regression (from Lovering et al. 2016). Each country's reactors were pared down to reactor classes of comparable technology. In the regression results, $n < 1$ means the reactors saw a larger effect from economies of scale; $n > 1$ implies diseconomies of scale. Negative learning rates mean costs increase with cumulative experience; positive rates mean they decrease. CANDU = Canada deuterium uranium; GCR = gas-cooled reactor; LWR = light water reactor; PHWR = pressurized heavy water reactor; PWR = pressurized water reactor

Summary of data				**Regression results**	
Fleet	**Specified reactor type**	**Number**	**Capacity range (MW)**	**Scaling factor, *n***	**Learning rate**
Canada	PHWR CANDUs	24	203–881	0.21***	−26%***
France1	GCRs, 1957–66	6	68–540	1.1†	32%†
France2	PWRs, 1962–91	59	280–1455	0.54***	−9.8%***
Great Britain	GCRs, 1957–1963	16	123–235	1.39†	3.0%†
India	All PHWRs	20	202–630	0.91†	−48%***
Japan	All LWRs	57	320–1325	0.7*	−24%***
South Korea	All PWRs (excl. Canadian PHWRs)	22	558–1340	0.47**	6.1%**
USA1	Demos, 1954–63	17	3–265	0.77***	10%†
USA2	Commercial LWRs, 1964–78	113	436–1304	0.26***	−23%***
West Germany	LWRs	35	62–1307	0.29***	−32%**

Note: *** indicates significance at the 99.9% confidence level, ** at the 99% level, * at the 95% level. † indicates insignificance at the 95% level.

and finds the microreactor OCC to be $35,000/kW—more than seven times the unit cost of the large reactor.

Two SMRs in the United States are currently going through licensing: NuScale's 60 MW LWR and Oklo's 1.5 MW fast reactor. Using our range of scaling factors from the historical data ($n = 0.2–0.8$), we estimate the FOAK costs for these two designs.

Scaling the AP1000 cost down to the 60 MW NuScale reactor would result in a FOAK cost ranging from $9800/kW to $56,000/kW, depending on the scaling factor. The upper figure appears unreasonably expensive, even for the most overbudget nuclear projects worldwide. Even the lower bound of nearly $10,000/kW is much higher than NuScale's estimate of $4400/kW (NuScale 2020), which is actually less than the realized cost of the AP1000. For a smaller unit, like Oklo's 1.5 MW reactor, the scaling relation yields even more unrealistic figures: $21,000/kW–$1.1 million/kW, depending on the scaling factor.

Of course, this scaling relation was meant to apply to similar technologies, and Oklo is a very different reactor from the AP1000. Even NuScale's LWR is likely too dissimilar to make a scaling relation applicable. However, it is useful to note that early solar photovoltaic (PV) panels started at similarly exorbitant costs—about $100,000/kW in the 1970s—and are now below $2000/kW (Nemet 2006). And while solar panels may seem like a "simpler" technology (that could therefore experience faster learning), the same cost trajectory is seen with the modern jet engine turbine, a very complicated piece of engineering with peak output >10 MW: its costs are now less than $1000/kW.

The discrepancy between modeled and projected FOAK costs highlights an important point: economies of scale and reactor capacity are not the only factors that will affect the cost of an SMR in comparison to a large NPP. NuScale (2020), for example, explains the lower cost estimate for its SMR based on design simplicity, as its proposed reactor has "no reactor coolant pumps, no external steam generator vessels, and no large-bore reactor coolant piping."

The IAEA report notes that other nonscaling factors (e.g., learning effects, expedited construction schedules, and rapid deployment rates) may outweigh most of the diseconomies of scale. The report looks at a case study comparing four 250 MW SMRs with a single 1000 MW NPP. Using the scaling equation above, it finds that the OCC of the FOAK SMR will be 74 percent higher, but the benefits from other factors reduce the total capital investment of the project to only 9 percent more than

TABLE 2 Estimated learning rates across non-nuclear electricity-generating technologies (data from Rubin et al. 2015). NGCC = natural gas combined cycle

Technology	**Learning rate**
Coal	5.6% – 12%
Natural gas, NGCC	−11% – 34%
Natural gas, turbine	10% – 22%
Wind, onshore	−11% – 34%
Wind, offshore	5% – 19%
Solar photovoltaic	10% – 47%
Biomass	0% – 24%
Hydroelectric	1.4%

the large-scale plant. The biggest contributor to that reduction is the learning associated with the construction of multiple units at the same site.

Learning Curves

As microreactors are deployed in series, unit costs are likely to decline in a process known as economies of volume or learning by doing. For large stick-built (i.e., nonmodular) power plants, the more common metric is to look at how capital costs decline with cumulative installed capacity. These so-called “experience curves” track industrywide learning across a country or region, rather than on an assembly line.

Early studies of cost trends for nuclear power found that the technology had experienced positive learning (Cantor and Hewlett 1988): construction costs decreased with increased firm experience. But more recent analyses have found negative learning, or forgetting by doing, where costs increase as firms or countries gain experience (Cooper 2010; Grubler 2010).[1]

Since no country has constructed a series of commercial SMRs, it is difficult to predict what the learning curve will be with factory fabrication.[2] While China has brought more than 40 reactors online over the last decade, with another 10 under construction, they were all large-scale stick-built construction projects.

Learning rates of other electricity-generating technologies may provide useful context. Rubin and colleagues (2015) aggregated learning rates from the literature and found rates ranging from −11 percent for onshore wind and combined cycle natural gas to 47 percent for PV solar panels (table 2).

Using our multifactor regression and a dataset of 369 reactors in 8 countries, our model finds that most fleets experienced statistically significant negative learning (table 1). To convert from our regression coefficient for country experience to a learning rate, we use the following two equations: $b = e^{\beta exp}$ and $LR = 1 - 2^b$.

With the exception of South Korea, none of the countries experienced significant positive learning—they all got more expensive with cumulative country experience. Great Britain, the US early phase, and the French early phase do show positive learning, but the result is not significant (likely because of the small number of reactors and confounding factors in those groups).

However, with stick-built large infrastructure like the large NPPs in this dataset, it is difficult to achieve the same degree of learning that is possible from serialized factory fabrication. (A recent survey of learning rates for energy technologies finds that learning effects are stronger for smaller-capacity technologies; Sweerts et al. 2020.)

Trade-Offs Between Economies of Scale and Learning Effects

How is it possible to determine the trade-offs between large and small reactors before building the first SMR? On one side are those who argue that bigger nuclear power plants, if built successfully, will be cheaper thanks to economies of scale. On the other are proponents of SMRs, who argue that the benefits of factory fabrication will accelerate learning effects and drive down costs with successive builds.

To start, we analyze the theoretical intersection of these two effects and put boundaries on the relevant parameters based on historical nuclear data and lessons from other electricity-generating technologies. To find this hypothetical crossover point, we assume two different nuclear reactor technologies: $Reactor_1$ is a conventional, large LWR, while $Reactor_2$ is an SMR. Using the standard learning curve formulation, the cost of the u^{th} unit built for each reactor is given by the equations for c_1 and c_2 below, where $c_{1,0}$ and $c_{2,0}$ are the FOAK

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[1] Nuclear power is not alone in experiencing negative learning rates: one study found that onshore wind and natural gas combined cycle plants also experienced negative learning over specific time periods (Rubin et al. 2015).

[2] An obvious exception is, of course, nuclear navies. The US, Russian, UK, and French navies have built small modular propulsion reactors for their nuclear submarines and aircraft carriers. While their cost data would be quite illustrative for commercial SMRs, attempts to obtain this information have been futile. Similarly, cost data are scarce for large-scale commercial power reactors recently built in China.

cost for each reactor, and b_1 and b_2 are the learning factors for each reactor.

$$c_1(u_1) = c_{1,0}u_1^{b1}$$
$$c_2(u_2) = c_{2,0}u_2^{b2}$$

To calculate break-even deployment, each learning curve must be formulated as a function of deployed capacity, rather than units, so we replace $u_1 = G/s_1$ and $u_2 = G/s_2$, where G is the total capacity deployed for each reactor, and s_1 and s_2 are the sizes of each reactor. Plugging these into the equations for c_1 and c_2 above, setting them equal, and solving for G:

$$c_{1,0}(G/s_1)^{b_1} = c_{2,0}(G/s_2)^{b_2}$$

$$G = \left(\frac{c_{2,0}\, s_1^{b_1}}{c_{1,0}\, s_2^{b_2}}\right)^{\frac{1}{b_1-b_2}}$$

This provides an analytical expression for the break-even deployment, G—that is, how many SMRs are needed to reach cost parity with the large reactor. The units of G will be the same as the units of s_1 and s_2, whether in kW, MW, or GW.

We apply these break-even equations to our 60 MW SMR and 1.5 MW microreactor examples to see the range of cost trajectories. If economies of scale are significant ($n = 0.2$) and learning is slow ($LR = 5$ percent), then it is infeasible for either reactor to reach cost parity with the AP1000 (if learning by doing is the only cost reduction mechanism). However, if economies of scale are less important ($n = 0.8$) and learning occurs faster ($LR = 25$ percent), then it would be necessary to deploy only 230 MW of the 60 MW reactor (4 units) or 32 MW of the 1.5 MW reactor (21 units).

And if these scaling relations simply do not apply (i.e., the technologies are too dissimilar), the simplified break-even equation can be used to understand the effects of reactor size and learning rate. Figure 2 shows the break-even volume for a 60 MW and a 1.5 MW reactor, assuming they both have FOAK costs of $11,000/kW (twice the cost of the AP1000). Even at slower learning rates, smaller reactors experience faster cost reductions, because more units are being built.

Policy Implications of a Transition to Small Modular Reactors

From the historical cost data, it is clear that most countries experienced economies of scale in their large reactor fleets, from a scaling factor of 0.2 in Canada to 0.8 in the United States. However, these were fleets of very similar technology, and it is unclear how well these scaling factors would apply to radically different types of advanced reactors and microreactors.

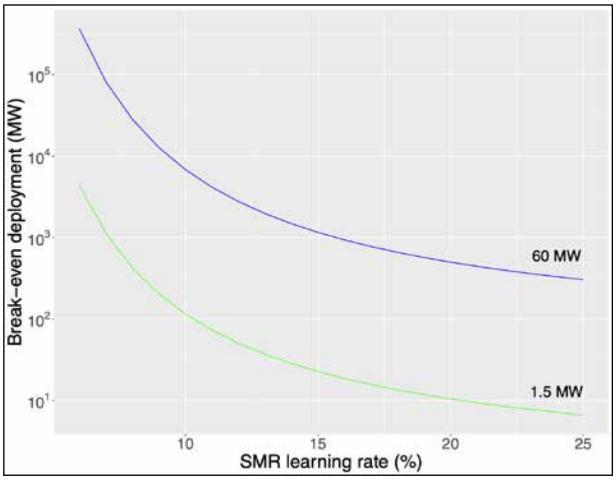

FIGURE 2 SMR deployment needed to reach cost parity with an AP1000 reactor, assuming it starts at $5500/kW, 1100 MW, and a learning rate of 1%. Break-even deployment is shown as a function of learning rate for the 60 MW reactor (in blue) and the 1.5 MW reactor (in green), assuming both start at $11,000/kW.

But the historical data also show that almost every country experienced negative learning (costs rose with cumulative country experience). In contrast, for other energy technologies that are modular, like gas turbines and solar panels, positive learning rates could be as high as 35–45 percent. With even modest learning rates of 10–20 percent, SMRs could reach cost parity with large reactors after a dozen units, even if they start out at twice the cost. This is certainly relevant to the fledgling industry, and has significant policy implications for the future competitiveness of smaller reactors.

While the goal of SMR and microreactor vendors may be full factory fabrication, the first few units will likely be built on site. These FOAK costs may be much higher than the eventual factory-fabricated units. Policies to support demonstration and deployment of SMRs should build in resiliency to higher FOAK costs, for example through direct government procurement, public-private partnerships for demonstrations, and loan guarantees for manufacturing facilities.

Vendors will likely need orders for tens of reactors to justify the investment in factory facilities to manufacture modular reactors. For comparison, Boeing and

Airbus line up a few hundred orders for new aircraft before the first one rolls off the assembly line (Lovering et al. 2017).

Federal policy that stimulated demand is ultimately what led to large cost declines for solar technologies (Nemet 2006). For small and microreactors, similar policies could include production and investment tax credits, federal power purchase agreements, state-level clean energy mandates, direct government procurement, and a streamlined licensing process for modular reactors.

Conclusion

The International Energy Agency and Nuclear Energy Agency argue that global nuclear capacity will need to double by 2050 to meet aggressive climate targets and match growing demand for energy (IEA and NEA 2015). This implies adding roughly 400 GW of new nuclear capacity and another 200 GW to replace retiring units. Most of the new capacity will likely come from large reactors, but if just 25 percent comes from SMRs that will equate to 2500 60 MW reactors or 100,000 1.5 MW reactors—large enough volumes to experience significant learning by doing and cost reduction.

While SMRs and microreactors are considered appropriate for niche markets today, this analysis shows that with significant volume, there is potential for their cost to decline enough to be competitive with large nuclear power plants. With targeted policies and fast learning rates, SMRs could reach cost parity with fossil fuels before 2050.

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Unique safety features of advanced reactors significantly reduce the risk of large-scale releases and community impacts.

Why the Unique Safety Features of Advanced Reactors Matter

José N. Reyes Jr., Finis Southworth, and
Brian G. Woods

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Finis Southworth

Brian Woods

Over the past two decades, significant efforts have been devoted to creating a new paradigm for the fabrication and deployment of nuclear power plants. These efforts include development of a variety of reactor designs aimed at increasing efficiency, flexibility, and safety.

From the standpoint of safety, an advanced reactor (AR) is defined as a nuclear reactor that, for all design basis accidents, ensures no offsite consequences and does so without requiring operator actions, AC or DC power, or the addition of coolant for an unlimited duration. Among these are small modular reactors (SMRs), factory-fabricated reactors that produce 300 MWe

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or less, enabling reduced construction times and more competitive overnight capital costs.

New SMR designs come in a variety of configurations, from a single small reactor to a multimodule plant. Some use different coolants, moderators, and fuels than the existing light water reactor (LWR) fleet. One of the most appealing features of the new designs is their unique safety features that enable off-grid operation for new applications and greater resilience to environmental impacts of climate change.

Quantifying the Safety of Nuclear Reactors

All nuclear reactor designs must satisfy three fundamental safety functions in the event of a significant abnormal event: stop the fission chain reaction, ensure adequate cooling of the nuclear fuel, and prevent the release of radioactivity into the biosphere. Nuclear reactors are designed with intrinsic safety features and engineered systems that are deterministically proven to achieve these three safety functions for specific scenarios.

> *The probabilistic risk assessment approach provides a quantitative measure of the risk of unwanted consequences.*

Because the number of possible scenarios and failure modes is very large and continuously evolving, the need for a more general quantification of nuclear safety was identified shortly after deployment of the first US commercial nuclear power plants in the 1960s. In 1975 the US Nuclear Regulatory Commission (NRC 1975) published the first probabilistic risk assessment (PRA) for nuclear power plants in its pioneering WASH-1400 report. PRA methods have greatly improved since then, but the fundamental PRA approach to quantifying nuclear plant safety remains the same. It is applied to all nuclear power plants in the United States and helps safety analysts identify potential areas for improvement in the plant design.

The PRA approach provides a quantitative measure of the risk of unwanted consequences. The magnitude of the calculated risk can then be interpreted as a measure of nuclear plant safety. In simplest terms, risk is the frequency of an event times the consequences per event:

$$Risk = (Event\ Frequency) \times (Consequences\ /\ Event)$$

For US nuclear power plants, the core damage frequency (CDF) is the figure of merit for the first level of PRA. The NRC's qualitative safety goals for all new reactors require that the CDF not exceed 10^{-4} events per reactor-year. That is, for new designs, a core damage event must not occur with a frequency of more than once every 10,000 reactor-years.

The safety features of advanced reactors are designed to reduce both the frequency of core damage events and their consequences beyond those of the existing nuclear fleet. The DOE-sponsored international effort for Generation IV reactors took this concept further by considering whether prevention of core damage required offsite power, onsite emergency AC power, or even DC power (DOE 2002). At the time, only one concept required no power to prevent core damage and that was the very high temperature gas-cooled reactor.

In this paper we focus on AR technologies of relatively higher maturity such as LWR-based SMRs, high-temperature gas-cooled reactors (HTGRs), and sodium-cooled fast reactors (SFRs).

Early Implementation of New Safety Criteria and Designs

After the Fukushima core damage of March 2011, the American Society of Mechanical Engineers (ASME 2012) called for reactors to meet new safety criteria that would ensure no social impact and obviate the need for significant land withdrawal due to an accident. The report has not gained traction in the US regulatory community. However, a NuScale SMR design submitted for certification largely follows the ASME safety strategy, HTGR designers are endeavoring to ensure "no social impact," and the Next Generation Nuclear Plant (NGNP) adopted the ASME design strategy in 2008, with the steam cycle HTGR. The NGNP must show that, both under design basis and beyond design basis events, no radionuclide releases offsite will exceed 10 CFR 20 limits.[1]

The PRISM (Power Reactor Innovative Small Module) design by General Electric is a small SFR with

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[1] Federal Code of Regulations, Title 10, Part 20: Standards for Protection against Radiation, online at https://www.nrc.gov/reading-rm/doc-collections/cfr/part020/.

inherent and passive safety aspects. The small size, passive decay heat removal, and inherent safety benefits of metallic fuel make SFRs very forgiving under severe transients. A few startup companies are pursuing SFRs both for their safety benefits and because of the ability to recycle the fuel and close the fuel cycle.

NuScale Power provided the PRA results for its 160 MWt SMR to the NRC as part of its design certification application,[2] showing that the CDF for all internal events was determined to be several orders of magnitude smaller than the NRC safety goal. While this significant reduction in CDF represents a major advancement in safety, the greater contribution relative to public perception of risk is the reduction in consequences: Even if a one-in-a-billion-year event were to occur, the dose at the site boundary would not likely exceed regulatory limits (NRC 2018; NuScale Power 2015). A site boundary emergency planning zone is much smaller than the 10-mile radius currently required for large 3000 MWt reactors. Furthermore, these rare events would evolve slowly such that the early release fraction, another NRC measure of safety, would essentially be zero.

The modular high-temperature gas-cooled reactor (MHTGR) design shows similar results. The MHTGR will use robust TRISO (tristructural isotropic) particle fuel in a low-power-density reactor core with a strong negative temperature coefficient and a solid high heat capacity moderator to ensure passive shutdown, passive heat removal, and low fission product release (INL 2011b). The PRA indicates significant margin to the NRC safety goals and no evacuation required beyond the site boundary as doses are less than prescribed by the EPA Protective Action Guides[3] (Inamati et al. 1987).

Advanced Reactor Safety Features

The numerous AR designs under development each have unique features that enhance safety through a few shared characteristics.

With SMRs, the amount of radioactive material and the corresponding heat generation rates range from 1/15 to 1/3 those of typical large reactors. The ratio is even smaller for microreactors (<5 MWe). This means that the source term available for release is inherently much smaller in each core. The smaller heat generation rates mean that free convection heat transfer and conduction are sufficient to remove heat without pumps needing external power.

Another characteristic of many advanced reactors is the compatibility of the coolant, moderator, and fuel, translating into much less severe off-normal events. In some AR designs, the safety of the reactor is not dependent on the coolant at all, since the methods of decay heat removal rely on phenomena such as conduction through solid material and thermal radiation. Some advanced reactors incorporate additional barriers to fission product release, including shield buildings or special fuel coatings (e.g., TRISO-coated particle fuel).

Given these characteristics, some advanced reactors do not require safety-related offsite or onsite power to keep their reactors cooled following an upset (e.g., station blackout, loss of coolant). Some might be housed in an underground structure or pool to enhance seismic resilience. The following sections briefly describe some specific AR safety features.

Accident-Tolerant Fuels

The severe reactor accidents at the Fukushima power station led many to question whether a better fuel system, with the same operational performance, could be used in light water reactors to enhance accident tolerance.

In advanced reactors the compatibility of the coolant, moderator, and fuel translates into much less severe off-normal events.

Research is underway to define fuels that would reduce chemical reactivity with steam, improve fuel thermal and cladding properties, and enhance fission product retention. Areas of focus are coatings on cladding, different cladding materials, additives to change fuel properties, and different fuel forms (Bragg-Sitton et al. 2014; DOE 2015; Zinkle et al. 2014). Lead test rods for some of these concepts have been loaded into existing US reactors for testing (Reed 2019; WNN 2020).

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[2] NuScale Power design certification application submitted to the US Nuclear Regulatory Commission; latest revisions available at https://www.nrc.gov/reactors/new-reactors/design-cert/nuscale/documents.html#dcApp.

[3] https://www.epa.gov/radiation/protective-action-guides-pags#pagmanual

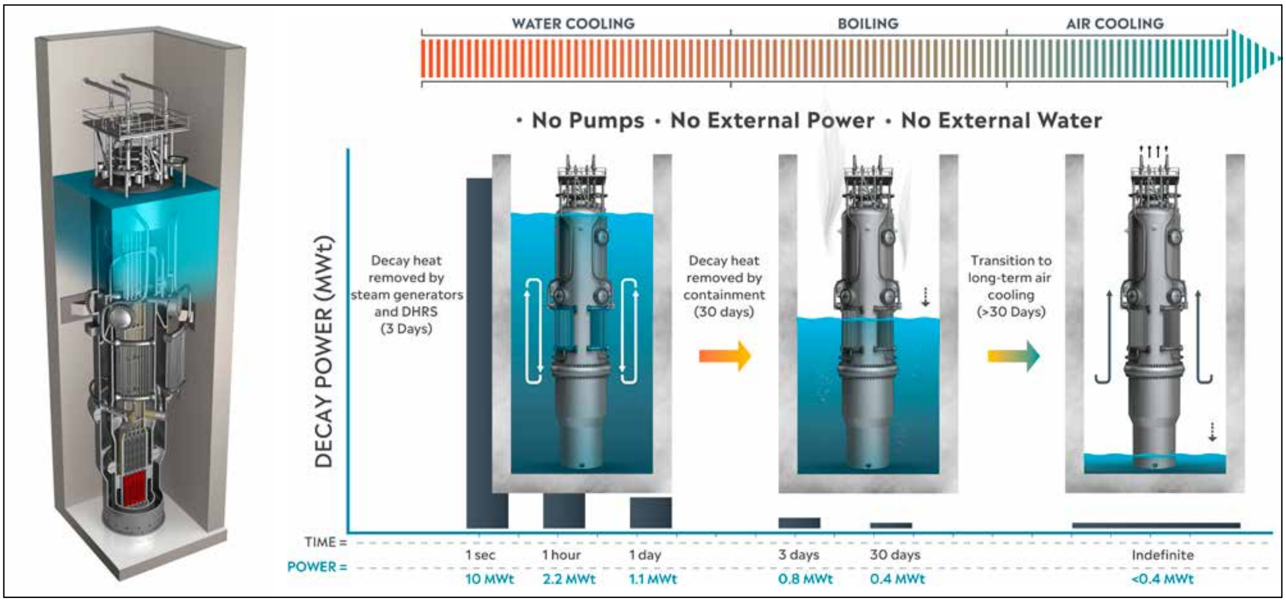

FIGURE 1 Illustrations of (*left*) a NuScale small modular reactor in its operating bay and (*right*) the passive transition from water-cooled to air-cooled decay heat removal. DHRS = decay heat removal system. Courtesy of NuScale Power LLC.

For sodium-cooled fast reactors, the two major fuel forms are mixed (uranium-plutonium) oxide fuels and metallic fuel. While the former has been studied extensively and remains the fuel choice internationally, in the United States metallic fuel was developed because it has relatively high heat metal densities and thermal conductivity, improved compatibility among the fuel system components, intrinsic passive safety characteristics, simpler fabrication processes, and less stringent quality control requirements than the oxide system. Metallic fuel is also of greater interest to SMR developers (Carmack et al. 2009; Ogata 2012).

TRISO fuel is used in high-temperature gas- and salt-cooled reactors in either cylindrical compacts or pebbles, each containing thousands of particles, and has been under study internationally for more than 50 years (IAEA 1997; Petti et al. 2012). It is fabricated with exceptionally high quality (defects are on the order of 1/100,000 particles) and is quite robust under irradiation and high-temperature accident testing. This has enabled the development of a "functional containment" safety strategy that uses this fuel as a nonstructural barrier to radionuclide release. A topical report on TRISO fuel performance is under review by the Nuclear Regulatory Commission (EPRI 2019).

Use of Containment as a Passive Heat Exchanger

Figure 1 presents the unique containment design for a NuScale SMR, a natural circulation reactor housed in an underground stainless steel–lined concrete pool in a seismic category 1 building resistant to massive earthquakes (>1.0 g at building frequency), very high winds (~470 km/h, exceeding those typical of category 5 storms), floods, and other natural disasters.

Coolant leaks from the reactor vessel into the containment vessel cannot cause the core to uncover nor the containment to overpressurize. The large surface area of the containment vessel, relative to the heat generated by the reactor core, will completely remove decay heat by condensation, conduction, and natural convection to the pool without operator action, AC/DC power, or the need to add water.

For modular high-temperature gas-cooled reactors (figure 2), decay heat can be removed from the vessel through radiation heat transfer from the outside reactor vessel wall to panels in the containment walls. Naturally circulating water or air (depending on the specific design) in the panels acts as the ultimate decay heat sink. Since radiation heat transfer is proportional to the surface temperatures to the fourth power, the removal of decay heat through radiation becomes significantly more effective as the temperature of the vessel wall increases. These gas reactors are designed to reach high temperatures to allow the efficient removal of decay heat through radiation. Even if the ultimate heat sink were to fail, the heat would radiate into the ground since the reactor is embedded below grade.

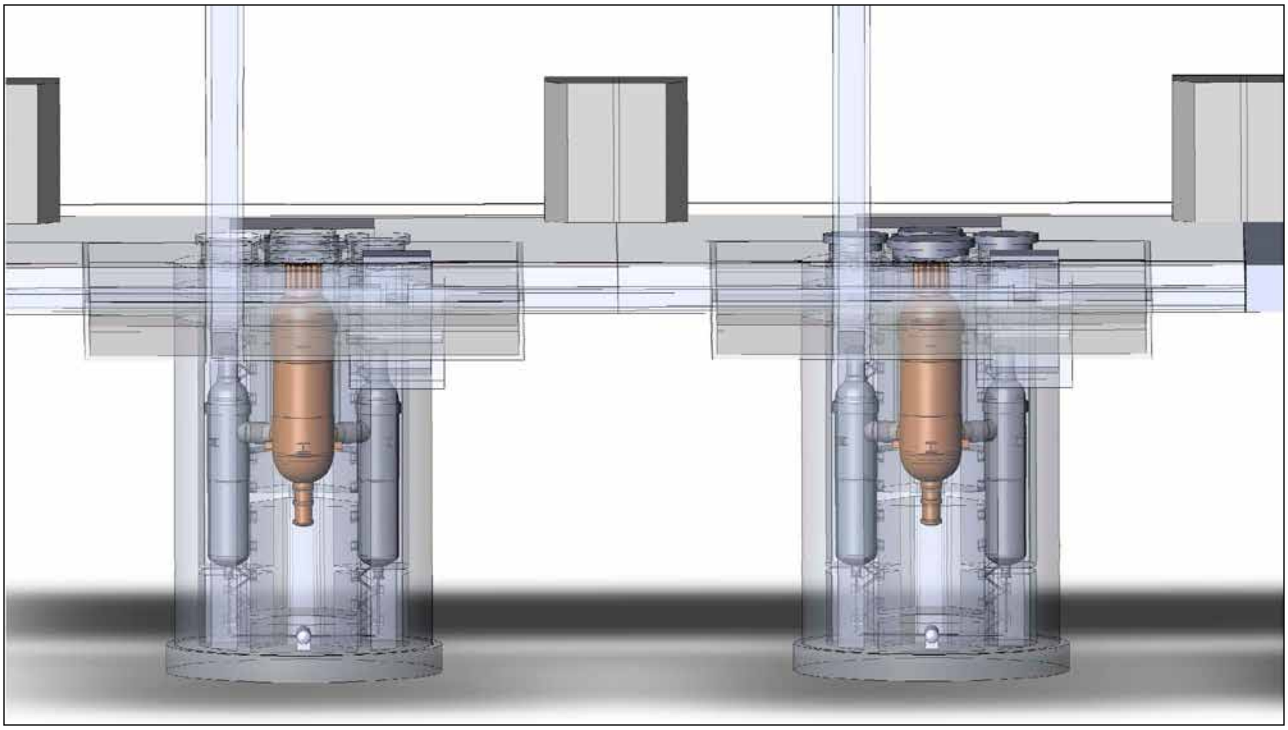

FIGURE 2 Modular steam cycle high-temperature gas-cooled reactors, showing their embedment. Courtesy of Framatome Inc.

Extended Coping Periods without Power or Operator Action

Advanced reactor designs extend the duration, or coping period, that a nuclear reactor can be cooled without the need for active power systems to replenish coolant. Some designs have a 7-day coping period, others can transition from water cooling to air cooling for an unlimited coping period.

Figure 1 illustrates this safety feature for an extended loss of onsite and offsite power. During normal operation, the safety valves are held shut or open against a motive force (i.e., spring or accumulator) using electrical power. Loss of power results in gravity insertion of the control rods and alignment of safety valves to their safe position, requiring no operator action. The reactor safety valves vent steam into the containment where it condenses on its inside surface. The condensate, driven by its gravity head, returns to the reactor vessel through recirculation valves, thus maintaining the core covered with liquid. Heat conduction through the containment wall and free convection on the outside surface of the containment remove the decay heat. Heat is also transferred to the pool via the steam generator using the decay heat removal system. After 1–3 seconds the core decay power drops to ~10 MW thermal, and after 1 day to ~1.1 MW thermal, typical of many university research reactors. The water level in the pool decreases over time due to boiling but heat transfer from the containment remains effective. After 30 days, the core decay power is only ~0.4 MW thermal such that radiative heat transfer and free convection of air on the outside surface of the containment vessel are sufficient to remove all the decay heat. This unlimited coping period is achieved without operator or computer action, AC or DC power, or the need to add water.

For MHTGRs, the high thermal inertia of the graphite core results in very slow transients and long coping times. Upon loss of either helium flow or helium inventory in the reactor, heatup of the reactor core under decay heat can take 1 to 2 days depending on the design. Peak fuel temperatures will remain below the level where significant fuel damage occurs. The reactor cavity cooling system passively protects the reactor silo concrete from overheating so that restart is enabled after repairs to the reactor coolant system.

Reactor Safety without Control Rods

Most AR cores implement very strong negative reactivity feedback mechanisms such that overheating the system results in a significant decrease in core thermal power, or complete shutdown of the reactor, even without the insertion of control rods. The moderator temperature, fuel temperature, and void reactivity coefficients are part of the inherent physics of the core design. The self-limitation of core power to a fraction of full power conditions means that the passive safety systems normally used to remove decay heat are fully capable of keeping the core cooled without control rod insertion.

Reactor Safety Demonstrations

Many AR safety characteristics have been demonstrated in existing reactors. Inherent and passive safety features were demonstrated in EBR-II, a small SFR with metallic fuel, in the 1980s. For MHTGRs, safety demonstrations of the strong negative reactivity feedback and loss of flow tests were conducted at the AVR pebble bed reactor in Germany, the HTR-10 pebble bed in China, and the high-temperature engineering prismatic test reactor in Japan (Buongiorno et al. 2018).

Specific Benefits of New Safety Features

Advanced reactor safety features offer a level of functionality, flexibility, and resilience not previously offered by nuclear power.

Off-Grid Operation

Because some AR designs do not require offsite power for safety, they could operate off-grid (NRC 2017) to provide heat and power for a wide range of industrial applications. For example, a "six-pack" NuScale plant could generate 200 metric tons of hydrogen per day using high-temperature steam electrolysis without carbon emissions. A single module could generate 60 million gallons of desalinated water per day for coastal cities (Ingersoll et al. 2014), and an HTGR, with its high outlet temperature (>750°C), would be well suited to supply process heat for the petrochemical industry as well as hydrogen production. (For a study of relevant markets and the associated economics, see INL 2011a.)

Off-grid operation also aids in adapting to the increased frequency of severe weather events due to climate change. If a severe weather event isolates a nuclear plant from the grid, instead of shutting down as required by existing regulation, an AR plant could remain in operational "island mode," dispatching power in increments as needed to support recovery of the grid. The ability to provide "first responder power" and black-start capability (the ability to resume power generation after a shutdown without relying on the electric grid) are due to the unique safety features of AR designs.

Climate Change Mitigation

Nuclear power must be a major component of strategies to combat climate change because it offers the greatest potential for reduced carbon emissions in the electricity sector. Both the International Panel on Climate Change (https://www.ipcc.ch/sr15/) and the International Energy Agency (IEA 2019) propose a significant increase in nuclear power to achieve global carbon emission reduction goals.

Because of their smaller footprint, reduced complexity, enhanced safety, and load following capabilities, small and midsize advanced reactors could play a major role in helping states reach their clean energy goals. Retired coal-fired plants could be repurposed, for example, and the use of existing infrastructure such as water supply, switchyard, and electric transmission lines would be a cost-effective approach to add carbon-free energy to the existing grid.

Highly Reliable Long-Term Power for Mission-Critical Facilities

Advanced SMRs and microreactors can provide highly reliable long-term power to mission-critical facilities such as hospitals, data centers, national laboratories, and military bases. For example, the NuScale 12-module plant design, with a redundant array of independent reactors and island mode capability, can provide 60 MWe to a dedicated microgrid at 99.98 percent reliability for the 60-year life of the plant. This corresponds to only 4 days with zero output over those 60 years (Doyle et al. 2016).

If a catastrophic event damages both the transmission grid and transportation infrastructure such that neither fuel nor power can be delivered to the site for a prolonged period, multimodule plants operating in island mode have a significant advantage. If the microgrid remains intact or can be restored, a 12-module plant can provide 120 MWe to the microgrid of a mission-critical facility for 12 years without the need for new fuel.

Conclusions

Advanced reactors offer unique safety features that significantly reduce both the frequency and the consequences of core damage events and will enable a new level of functionality, flexibility, and resilience for nuclear power. Some features may prevent exceeding regulatory doses at the site boundary even in a highly unlikely event that exceeds design basis.

The improved features may expand the role of nuclear power in climate change mitigation, for example reducing CO_2 emissions through the repurposing of coal-fired power plants located near population centers. They also enable a variety of off-grid applications, such as hydrogen production, desalination, first responder power for grid recovery, and power to microgrids for mission-critical facilities.

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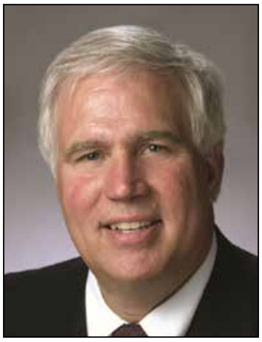
Advances are needed to effectively adapt regulations for proposed advanced reactors.

Regulatory Innovation to Support Advanced Reactors



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Richard A. Meserve

All commercial nuclear power plants operating in the United States are light water reactors (LWRs), in which the coolant and the moderator are ordinary water. Many vendors seek to commercialize different types of reactors—so-called “advanced reactors”—that are radically different from existing LWRs. Some advanced reactors (ARs) will use gas, liquid metal, or molten salt as a coolant and simplified, inherent, passive, or other innovative means to accomplish their safety functions. Some will have a fast neutron spectrum (LWRs have a thermal neutron spectrum), some will operate at or near atmospheric pressure, and some will be much smaller than current-generation LWRs.

Advanced reactors promise lower cost per kWh, higher operating temperatures (providing greater thermodynamic efficiency and enabling expanded process heat applications), longer or more flexible operating cycles, and reduced waste production. But the unique aspects associated with these designs present a challenge because the existing regulatory system focuses on ensuring the safety of LWRs.[1]

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[1] A summary by the Nuclear Regulatory Commission of its various activities to deal with the regulatory challenges is available at https://www.nrc.gov/reactors/new-reactors/advanced.html. A survey of issues is at https://www.nrc.gov/reactors/new-reactors/smr.html.

Licensing Procedures

Existing Licensing Approaches under the Code of Federal Regulations

All of the existing US reactors, with the exception of two now under construction in Georgia, were licensed by the Nuclear Regulatory Commission (NRC) under a regulatory scheme defined in the Code of Federal Regulations, 10 CFR Part 50 (NRC 2018a). Under this licensing paradigm, an applicant first obtains a construction permit and then, while construction is underway, seeks an operating license.

The regulatory procedures associated with a construction permit involve a review of the suitability of the site and of the general appropriateness of the reactor technology. A thorough review of this technology is part of the evaluation of an application for an operating license. At both stages of the process, affected individuals and organizations can challenge the NRC staff's proposed decisions, which can result in extensive hearings before the commission's Atomic Safety and Licensing Board (ASLB), followed by review by the NRC staff and the courts.

Under the Part 50 process the NRC can deny an operating license or require substantial and expensive retrofits of an already built reactor. This occurred for reactors that were under construction at the time of the Three Mile Island accident (Walker and Wellock 2010). As a result, in the late 1980s the NRC established a second licensing process (Part 52) to reduce the financial and delay risks associated with Part 50.

Under Part 52 (the regulatory approach used for the two reactors in Georgia), the licensing process can involve three components (NRC 2018a). A vendor of a reactor technology can pursue a design certification (DC) for the full design of the plant's nuclear island or a standard design approval (SDA) for a significant portion of a design. After review of the adequacy of the design to achieve safety requirements, the NRC can promulgate a rule certifying it, which may occur long before there is a commitment to actually construct the design.

A prospective licensee can also obtain an early site permit (ESP), which defines the "environmental envelope" to be satisfied by a reactor at a particular site. An ESP can be sought before selection of the reactor technology or even a firm commitment to pursue construction.

Finally, a prospective licensee can obtain a combined license (COL) that authorizes both construction and operation (10 CFR 52.97(b)). However, the licensee is not permitted to load fuel and commence operations until the NRC determines that the inspections, tests, analyses, and acceptance criteria (ITAAC) specified in the license have been satisfied (10 CFR 52.103(g)). A COL applicant need not have an ESP and a DC (or an SDA), but if it does, these authorizations can be incorporated in the application.

The licensing process for current reactor designs allows an applicant for construction to avoid some regulatory risk.

Each of the Part 52 processes enables an applicant for construction to avoid regulatory risk. Matters resolved in connection with an ESP or DC cannot be reexamined (absent new and significant information that could call into question the previous resolution of an issue), which limits the scope of the licensing proceeding for a COL.

A COL by itself serves to avoid much of the regulatory risk associated with a Part 50 license because it is issued before safety-related construction starts (absent construction authorization by the NRC), reducing the danger of regulatory changes. The risk is not eliminated because of the need to satisfy the ITAAC, and in any event the NRC can always require "backfits" to conform to new regulatory requirements at any reactor if necessary to provide adequate protection of public health and safety or if the weighing of comparative costs and benefits justifies a change (10 CFR 50.109).

A drawback of Part 52 is that a DC or COL approval "freezes" the design under circumstances in which the first construction of a new design may expose the need for changes that were not anticipated in the approval process. Changes in the approval can result in expense and delay.

Neither Part 50 nor Part 52, as originally contemplated, meets the licensing needs of those pursuing advanced technologies. Moreover, other aspects of current regulatory processes present challenges.

Staged Licensing

Part 50 can present unacceptable financial risks because the determination of whether a given design can be licensed by the NRC is resolved only when an operating license is pursued. An applicant pursuing approval of an AR design confronts significant regulatory risk after substantial cost has been incurred because of the absence of precedents as to how the NRC will view novel design features.

Furthermore, although a DC under Part 52 provides some earlier certainty, it requires a complete design (or a significant portion of the design in the case of an SDA) to be defined in the application. The vendor cost for a DC is very large (many times the NRC fees) because of the necessity for submission of a complete design for NRC review, along with all the necessary test data and analyses (10 CFR 50.43(e)). Design certification thus involves a formidable front-loaded investment (SEAB 2016).

Investments in advanced technologies are typically made in stages or graduated steps as risks are retired. Some of the risks associated with the pursuit of an AR technology are technical, some reflect market risk, and some are regulatory. Regulatory risk arises because the NRC might reject a new approach or impose requirements that make the design unattractive in the market, or because the cost and delay of NRC review may be more than the applicant can bear. Regulatory risk is inimical to investment because it may be difficult for an applicant to assess (SEAB 2016).

An optional new licensing pathway will be technology-inclusive, risk-informed, and performance-based.

For these reasons, some have urged a regulatory process in which issues are resolved in a stepwise fashion, to be compatible with a staged series of investments (Finan 2016; Merrifield 2016). In 2019 Congress passed the Nuclear Energy Innovation and Modernization Act, which directs the NRC to proceed with staged licensing and, by 2027, to promulgate an optional new licensing pathway (Part 53) that is technology-inclusive, risk-informed, and performance-based (NEIMA 2019).

While the NRC prepares for the rulemaking, it is adapting current licensing pathways to achieve staged licensing using existing regulatory vehicles—technical reports, topical reports, exemption approvals, white papers, and possibly generic environmental impact statements—to provide early guidance to vendors. It has encouraged vendors to consult with the staff to surface important issues at an early stage and to establish a licensing project plan that reflects a common understanding of the responsibility of each party and sets a licensing schedule (NRC 2019a, 2020a).

Although there still may be regulatory uncertainty—the NRC staff, the commission, the Advisory Committee on Reactor Safeguards, the ASLB, and the courts are not legally bound by some of these early staff determinations—vendor concerns about regulatory risk have been reduced (INRC 2020a).

Fees

Under existing law the NRC must recover 90 percent of its budget from fees charged to current licensees (e.g., annual fees for various classes of licensees) and through hourly charges for work to benefit a specific licensee or applicant. Many advanced reactors are much smaller than existing reactors and, in recognition of this fact, the NRC has completed a rulemaking to adjust its annual fees once such plants are in operation (NRC 2016a).

But recent experience shows that the hourly fees can present a serious challenge, as reflected in the costs for review of LWRs. The NRC review of DC applications has resulted in fees from $14 million to almost $68 million, a COL can involve fees from $22 million to $55 million, and an ESP may result in fees from $5 million to $14 million (NRC 2020b). It may be hoped that the simplicity of some of the AR designs and the promise of increased safety will reduce the cost of review, but these designs present unique issues that may make this unlikely, at least in their first regulatory encounter. Moreover, these costs reflect only NRC fees and do not include the much greater costs that applicants confront in collecting the data, completing necessary analyses, and assembling the case for licensing.

The fees present a particular challenge for applicants with advanced approaches because many vendors are small companies whose resources must be carefully husbanded. Some cost sharing was provided by the Department of Energy (DOE) for the DC fees of a small modular reactor (SMR) and broader cost sharing of fees may be essential on an ongoing basis (INRC 2020b). Indeed, Congress recognizes that cost sharing of the even greater overall cost of the early stages of developing and building an advanced reactor may be necessary to set the stage for commercial exploitation. Congress appropriated $230 million in the FY2020 budget for the DOE to start a demonstration program for advanced reactors, including $160 million for the first year of funding to build two AR demonstrations (DOE/NE 2019, 2020).

Prototype Plants

Data to establish the safety of an advanced reactor design, including in particular the examination of the interaction of subsystems (so-called integral effects), may be insufficient to allow licensing of a design in its contemplated commercial configuration. If an applicant determines that sufficient data are not available from component, integral, and separate effects testing to demonstrate safety features, an applicant may propose that the planned first-of-a-kind reactor be licensed and tested as a prototype plant (NRC 2017a).

A prototype plant may be identical to a proposed standard plant design in all features and size but include additional safety features to protect the public and the plant staff from the possible consequences of accidents during the testing period. The plant can be used to test new or innovative design or safety features and computer models. The resulting reduction in uncertainty can then be used to justify less restrictive reactor protection systems, higher operating powers, higher operating temperatures, or longer operating cycles for subsequent plants of the same design.

A prototype plant can thus be a transitional step between the development of a particular reactor technology and full commercial deployment. The construction of a prototype to support NRC licensing has not been undertaken, but may be an attractive approach for some vendors (Buongiorno et al. 2018).

Regulatory Approach to Safety

The NRC is tasked to provide reasonable assurance of adequate protection of public health and safety and of the environment. This objective is achieved by ensuring the means to control reactivity, remove heat from the reactor and waste stores, and limit the release of radioactive material. A reactor design must provide high confidence that there are means to prevent and mitigate any failure to achieve these fundamental safety functions.

A central element in design and operations is a philosophy of defense in depth (DID)—layers of diverse, independent, and redundant protections and barriers to prevent or minimize a radioactive release. In addition to careful design, safety depends on close attention to safety culture, radiation protection, quality assurance, operating experience, training, maintenance and surveillance, operational excellence, and emergency preparedness (INSAG 1999).

> *Congress recognizes that cost sharing in the early stages of developing and building an advanced reactor may be necessary.*

The detailed means to achieve the safety objective for most operating LWRs were based on deterministic analyses and judgments, resulting in prescriptive requirements promulgated in the 1960s and ’70s. The capacity to undertake sophisticated probabilistic analyses of accident sequences was subsequently developed, along with quantitative health objectives (NRC 1986). The probabilistic analyses provide a means to determine whether requirements for meeting safety objectives should be enhanced or can be relaxed.

At the same time, the regulatory philosophy evolved to emphasize outcomes rather than prescriptive requirements (Walker and Wellock 2010). Today the early regulatory requirements for LWRs are supplemented with risk-informed and performance-based requirements (Kadambi et al. 2019; NRC 1995).[2]

In fulfillment of an NRC (2007) feasibility study, a profound new approach to the determination of the regulatory requirements for advanced reactors is being formulated with support from industry and DOE. The Licensing Modernization Project seeks to use probabilistic insights for the selection of licensing basis events (considered in the design and licensing of a plant); for the classification of structures, systems, and components (SSCs) to ensure that safety-significant components can each fulfill their function; and for the determination of

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[2] The history of risk-informed regulation is available at https://www.nrc.gov/about-nrc/regulatory/risk-informed/history.html.

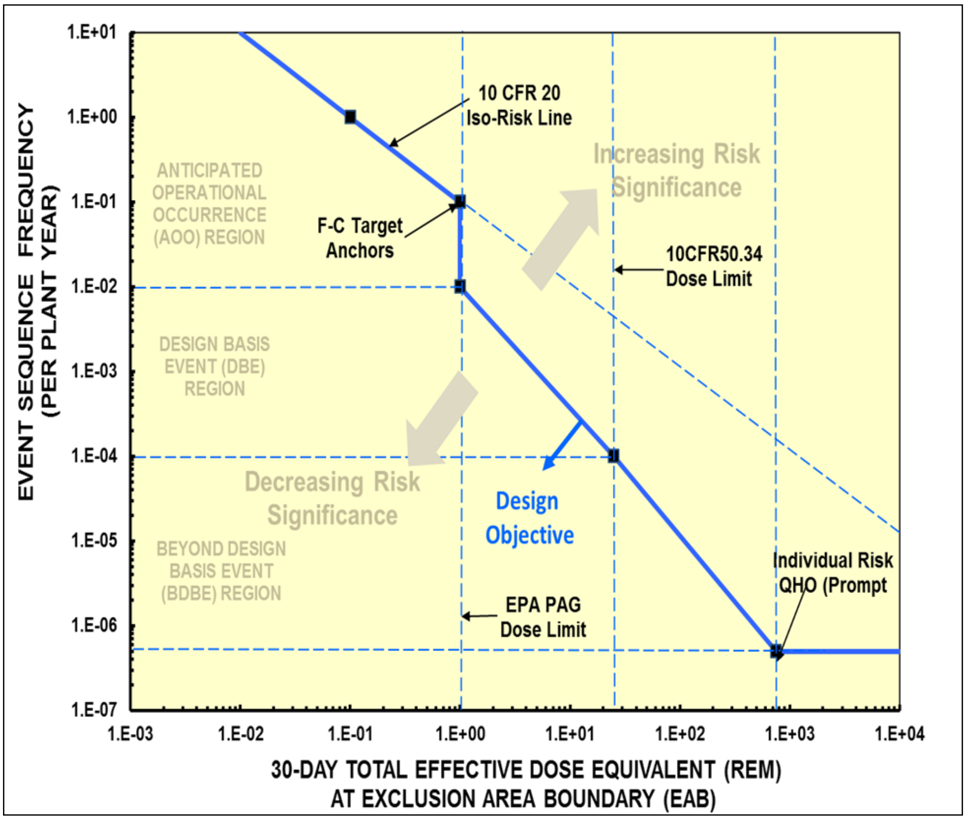

FIGURE 1 Frequency-Consequence (F-C) Target. Consequence is defined in terms of dose. The blue line is determined by various regulatory limits and the design objective is to stay to the left (i.e., the lower dose side) of that line. CFR = Code of Federal Regulations; PAG = Protective Action Guide; QHO = quantitative health objectives; REM = roentgen equivalent man. Reprinted from NEI (2019).

DID adequacy (NEI 2019; NRC 2019b,c, 2020c). Judgment still plays an important role, but principally to provide margin to deal with uncertainty.

The process is guided by a frequency-consequence curve (figure 1) to ensure that more frequent event sequences have low consequences; somewhat greater consequences can be permitted for infrequent (or rare) event sequences. The aim is a risk-informed, performance-based, and technology-inclusive means to guide licensing by way of a logical, systematic, and reproducible process. The NRC has endorsed the process and is allowing vendors to use it, rather than the detailed licensing guides established for LWRs, to support the licensing of advanced reactors (NRC 2020d).

Specific Technical Challenges

Because advanced reactors can present very different risks from those presented by LWRs, the designer and the NRC must confront specific technical issues in licensing, such as the following.

Safety Systems

Existing reactors have DID systems to ensure safety. For example, all LWRs have independent systems to inject water into the reactor and cool the core in the event of a major pipe break (10 CFR 50.46). These systems typically depend on "active" components (e.g., pumps, automatic valves, and safety-related AC power) to fulfill their function.

One common characteristic of both advanced reactors and advanced LWRs (such as those nearing completion in Georgia) is reliance on passive systems that use gravity, natural convection, or pressure gradients to meet the safety objective. Such systems simplify the reactor design in ways that may reduce cost. They also can have important spin-off impacts, such as the determination that the passive safety capabilities of the NuScale design (a light water SMR) justified relaxation of the safety requirements for the electrical systems that provide emergency power (NRC 2019d).

Detailed analyses and data are required to show the effectiveness of passive systems. Moreover, while AR designs may eliminate the need to consider some LWR-based accident concerns, some designs may present new safety issues, such as sodium-water reactions in sodium-cooled fast reactor designs.

Siting

The behavior and potential releases and consequences of events and accidents at advanced reactors may differ significantly from those of large LWRs. Many advanced designs have relatively small cores as well as other features (such as passive decay heat removal) that are anticipated to result in smaller and slower accident releases. This means that advanced reactors might allow reduced distances to exclusion area boundaries and low-population zones, and potentially increased proximity to population centers (NRC 2016b, 2017b, 2019e). This opens the prospect that advanced reactors might replace fossil plants, which are often located in the vicinity of dense populations, and thereby make use of existing energy transmission infrastructure.

Security

The current physical security framework for large LWRs is designed to protect the plant features that provide fundamental safety functions. Advanced reactor designs are expected to include attributes that result in smaller and slower releases of fission products in the event of any loss of safety functions (NRC 2018b).

There is an opportunity with advanced reactors to consider security requirements in the design to a greater extent than was the case with LWRs (NEI 2016). For example, protection from an aircraft attack can be enhanced through below-grade installation of safety-significant SSCs. Similarly, enhanced safety systems could limit or delay the radiological risk arising from an attack. These changes may improve security and reduce reliance on security personnel—a meaningful part of the operating cost at existing LWRs—to prevent or mitigate attempted radiological sabotage. The NRC is pursuing a limited-scope rulemaking to address this issue (NRC 2019f).

Containment

Much of the construction cost for LWRs is associated with the massive reinforced concrete structures that are intended to provide the final barrier to the release of radioactive material in the event of an accident (Buongiorno et al. 2018). The operating conditions, coolants, and fuel forms of non-LWR technologies differ from those of LWRs and may allow or possibly require different types of containments. If a design can retain radioactive materials by using other barriers, the building enclosing the reactor may not be necessary to fulfill the containment function for some or all event categories (NRC 2018c, 2019g).

NRC staff are applying functional containment performance criteria, opening the prospect of avoidance of the significant cost of existing containments for AR designs that can provide alternative means for preventing or mitigating large radioactive releases (NRC 2020c).

Fuels

Existing LWRs use uranium-oxide pellets enriched in U-235 to about 5 percent, with a zirconium alloy fuel cladding. Several fuel types are proposed for advanced reactors, including tristructural isotropic (TRISO) particle and metallic fuels, enriched in U-235 in some cases to nearly 20 percent (GNI 2019). Some of the contemplated molten salt reactors even have the nuclear fuel dissolved in the molten salt coolant.

The NRC requires that all fuels display accident tolerance while meeting other performance standards, such as retention of fission products and cladding-coolant compatibility. One of the challenges that must be overcome is the limited experimental data on some non-LWR fuel types. This is likely to be a particular challenge for some designs because of the need for extensive irradiation to provide the data necessary to support the safety case.

Conclusion

There is great interest in the commercialization of advanced reactors, but their licensing presents serious regulatory challenges. The business case for many of the new designs assumes that many existing regulatory requirements can be relaxed or modified in light of their inherent safety features.

Beyond procedural and technical challenges, there are needs for NRC staff training on unfamiliar technologies, the development of analytical tools, advances in computer codes and standards, and coordination among industry, DOE, national laboratories, and international organizations (NRC 2020a). Fortunately, the commercial sector, DOE, and NRC are working to address these challenges and their complicated dimensions.

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Societal and ethical issues associated with nuclear energy should be taken into account, recognizing that they may well change over time.

Engineering and Social Responsibility

Accounting for Values in the Development and Design of New Nuclear Reactors

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According to a recent report of the Intergovernmental Panel on Climate Change (IPCC 2018), nuclear energy will play an important role in all scenarios in which global temperature rise is limited to 1.5°C above pre-industrial levels. One scenario even anticipates a sixfold increase in nuclear energy by 2050. These projections raise questions about the types of nuclear energy and nuclear reactors that might help achieve this goal.

Proposed new reactor designs either incrementally improve existing Generation II light water reactors or are based on radically differently designs that aim, for instance, for small-scale production of nuclear energy (e.g., Lovering and McBride 2020). Others explore alternatives such as molten salt as a nuclear fuel and coolant (e.g., Meserve 2020).

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Table 1 Values for nuclear energy (Taebi and Kadak 2010; Taebi and Kloosterman 2015). Sustainability may be seen as an overarching value, particularly for the last three rows in this table.

Value	Explanation
Economic viability	Affordability of investments for developing, building, maintaining, operating, and decommissioning nuclear reactors as well as affordable energy prices
Safety	Protection of people from accidental and unintentional harm over the reactor life cycle (e.g., including storage of nuclear waste)
Security (including nonproliferation)	Protection of people from intentional harm due to nuclear energy production (e.g., arising from weapons proliferation, theft or sabotage of nuclear materials, cybersecurity threats)
Resource durability	Continued availability of natural resources for nuclear energy production or the ability to regenerate such resources
Environmental benevolence	Protection of the environment from harm (including climate change, thermal pollution, or other emissions)
Intergenerational justice	Protection of the well-being of future generations (in particular related to nuclear waste and greenhouse warming)

New reactor designs often spring from specific value considerations. Apart from CO_2 reduction and climate change more broadly, considerations of cost and safety play a role in choices among nuclear options (Ingersoll et al. 2020). We argue that, for a full picture of the societal and ethical issues associated with nuclear energy, additional values should be taken into account, recognizing that they may well change over time.

Values in Nuclear Energy

In addition to economic viability, safety, and CO_2 reduction, various other values are at play in nuclear energy and in choices among nuclear options (table 1). One such value is nonproliferation: the development and use of civil nuclear energy should not contribute to the (further) spread of either nuclear weapons or the knowledge and materials needed for these weapons. Nonproliferation has been an important value since the start of civil nuclear energy after the Second World War.

More recently, other security concerns have become more prominent. Whereas the value of safety is in preventing unintended harm (e.g., from a reactor accident), security concerns protection from intentional harm. Nuclear reactors and other nuclear facilities may be the target of terrorist or cyberattacks or theft of nuclear materials. The Nuclear Security Summits initiated by President Barack Obama aimed to limit these and other security concerns associated with nuclear materials and installations.

Sustainability

The current emphasis on CO_2 reduction is part of a broader value concern that can perhaps best be categorized as sustainability, which encompasses different types of more specific values. It is usually defined following the definition of sustainable development by the Brundtland committee: “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (WCED 1987, p. 41).

While sustainability is often used in a dichotomous mode in public debate about whether certain energy technologies are sustainable or unsustainable, it is a rich notion that could enable serious ethical assessments of energy technologies, including nuclear (Kermisch and Taebi 2017).

The broad definition of sustainability also encompasses values such as environmental benevolence and resource durability. Environmental benevolence refers to concerns related to climate change and CO_2 reduction as well as other possible environmental effects—positive or negative—from the use of nuclear reactors (e.g., thermal pollution). Resource durability refers to the continued availability or regeneration of nuclear energy resources, such as uranium. Uranium is abundantly available in the Earth’s crust and in seawater, but its economically affordable availability depends on the price of extraction. Resource durability may be a reason to look for other fissile materials such as thorium, or for ways to regenerate fissile materials through reprocessing (although this may also lead to additional proliferation concerns).

In the Brundtland definition, sustainability refers not only to environmental concerns but also to issues of intragenerational and intergenerational justice. The latter is a particularly important value in nuclear energy deployment and waste management.

Trade-Offs

Current reactors produce waste that remains radiotoxic for several hundred thousand years and therefore requires very careful storage over a very long period. This obviously raises questions about the level of protection owed to future generations. At the same time, nuclear energy offers possibilities to reduce greenhouse gas emissions and associated global warming, benefiting future generations. For these reasons, it is appropriate to recognize that different nuclear fuel cycles and nuclear waste management options might affect the interests of short- and long-term future generations differently (Kermisch and Taebi 2017).

The choice for a (future) nuclear fuel cycle or reactor may best be considered in terms of important values at stake. Sometimes values support each other (e.g., the economic viability and resource durability of uranium), in other cases they may conflict. Systematically accounting for values in the design of new technologies requires the adoption of an approach such as value-sensitive design.

Value-Sensitive Design

Value-sensitive design was developed in the 1990s to better take into account values of moral importance in the design of computer systems (Friedman and Hendry 2019). Since then, variations have been developed (e.g., design for values); more specific methods and tools have been proposed; and applications have expanded to a variety of engineering domains, including software development, architecture, water engineering, energy systems, biotechnology, nanotechnology, and nuclear technology (van den Hoven et al. 2015).

At the core of value-sensitive design is a tripartite method of empirical, conceptual, and technical investigations:

- Empirical investigations involve mapping relevant stakeholders and inquiring into the values that they consider important and how they understand these values.
- Conceptual investigations involve a further definition and conceptualization of the values at stake (think, for example, of the Brundtland definition of sustainability), considering tensions between values and possible ways to address them (e.g., through trade-offs between them).
- Technical investigations seek to (i) discover value concerns in current technical choices and designs and (ii) translate relevant values into technical features so that the new technology design respects these values.

These three types of investigations require different types of expertise. Generally speaking, technical investigations primarily require engineering and scientific expertise, empirical investigations require expertise in social science, and conceptual investigations mainly draw on philosophical and legal expertise. Moreover, the three types of investigations are not just phases of the design process that can be done separately: they require interaction and iteration in an interdisciplinary approach.

There are at least three ways that values can play a role in nuclear energy. First, they may be translated into design heuristics and requirements to guide the design and development of new technology (van de Poel 2013). For example, nonproliferation may be specified in the (design) requirement that a nuclear reactor not produce materials that can be used to manufacture nuclear weapons or that those materials not be easily separable. In a pebble bed reactor, for instance, plutonium is produced by fissioning U235, but this plutonium cannot be easily (and efficiently) separated from the silicon-coated pebbles, so this reactor better meets the value of nonproliferation (Taebi and Kloosterman 2015).

Second, values may be used in development and design choices as criteria to compare and choose between options. Different fuel cycles (Taebi and Kadak 2010) and proposed reactor designs (Taebi and Kloosterman 2015; table 2) have been assessed for how well they meet a range of values.

Third, values may inspire new areas of research or new design approaches. For example, when the first risk assessments of nuclear reactors were done, there was no

Table 2 Three future reactor designs scored on four important values: safety, security, sustainability, and economic viability
(Taebi and Kloosterman 2015). GFR = gas-cooled fast reactor; HTR-PM = high-temperature reactor pebble bed module; MSR = molten salt reactor

	HTR-PM	GFR	MSR
Safety	++	–	+
Security (mainly nonproliferation)	+	–	–
Sustainability (mainly resource durability)	–	+	++
Economic viability	+	0	–

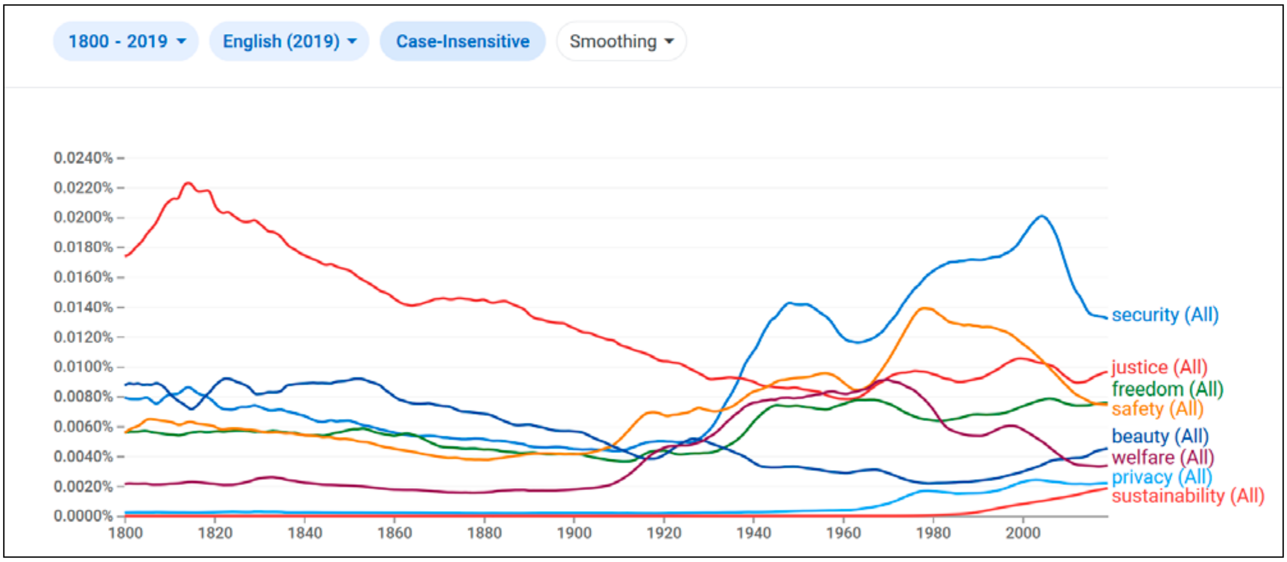

FIGURE 1 Societal value changes in security, justice, freedom, safety, beauty, welfare, privacy, sustainability, 1800–2019. The analysis was done August 13, 2020, with Google Books Ngram viewer (https://books.google.com/ngrams).

full-fledged theory of reactor operation and historical accident data were not available. This triggered the development of probabilistic risk assessment (PRA), a method for estimating risks that was first applied in the so-called Rasmussen study (NRC 1975). While PRA has not eliminated the large uncertainties in safety risk estimates for nuclear reactors (van de Poel 2015), it has become an important assessment and design tool inspired by the value of safety.

Changing Values

One issue that is particularly important in the design of technologies with long life cycles is that values may change over time (van de Poel 2018) and in different contexts, such as, in the case of nuclear energy, society as a whole, societal debate about nuclear energy, scholarly literature on nuclear energy, and the day-to-day operation of nuclear reactors.

For society as a whole, figure 1 provides a rough indication of changes in the relative importance of societal values over time. One interesting development is the emergence of the value of sustainability, which has gained traction since the late 1980s. Although references to what is now called sustainability can be found going back to antiquity (Du Pisani 2006), the value became prominent only in the late 20th century because of increasing environmental degradation and the need to balance economic development with environmental protection. These general developments have also influenced the field of nuclear energy. For example, there is a growing emphasis on the role of nuclear energy in reducing CO_2 emissions.

Societal debate about nuclear energy reflects broader societal developments (e.g., the rising interest in sustainability since the 1980s) as well as other dynamics. For example, the emphasis on safety in this context is driven partly by the large nuclear accidents at Three Mile Island (TMI; 1979), Chernobyl (1986), and Fukushima (2011). Moreover, nuclear energy raises its own specific moral problems, like nuclear waste and proliferation, which means that the values in this context will not be exactly the same as in general society.

An important question is how the societal discussions affect the scientific nuclear community and the direction of technical research and design. Figure 2 shows the percentage of scientific articles on nuclear energy that address a specific value: safety, security, sustainability, economic viability, and intergenerational justice. The figure is based on a topic model that traces both explicit and latent or implicit discussions of a value in documents (de Wildt et al. 2018, 2020).

Figure 2 shows a number of interesting things. First, the growing attention to safety reflects, at least in part, societal discussions and concerns in the wake of the three large nuclear accidents. However, other factors played a role as well.

Concern about the risk of accidents led to a shift from active to passive safety systems, which rely on natural laws,

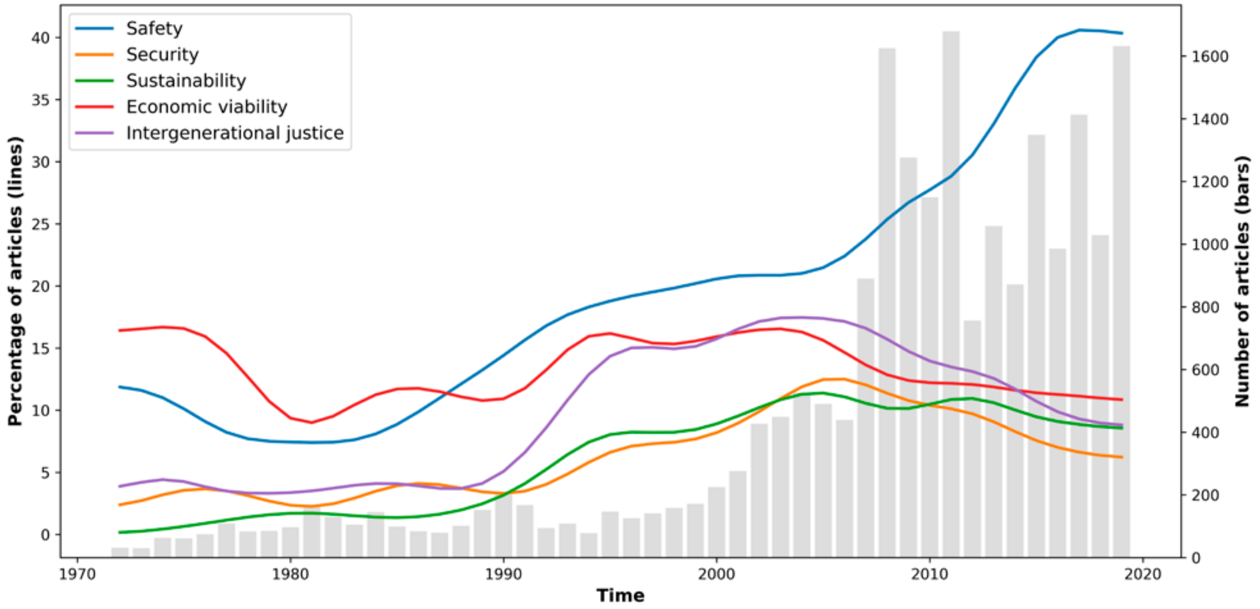

FIGURE 2 Percentage of 21,731 scientific articles addressing both explicit and latent values for nuclear energy over time (1972–2019). See de Wildt et al. (2020).

such as the law of gravity to help water flow to the reactor core if the temperature increases. The most advanced safety conceptualization is inherent safety that relies on design choices that eliminate certain risks altogether. A high-temperature reactor pebble bed module (table 2) is designed—in terms of the size and shape of the reactor and the reactor fuel (silicon-coated pebbles)—so that it can never reach temperatures at which its core could melt. The move toward passively safe reactors was mainly an attempt to guarantee public acceptance, especially for small-scale reactors that could be built closer to residential areas, with the benefit of energy provision in urban areas (Taebi and Kloosterman 2015).

What is further remarkable in figure 2 is the relatively low emphasis on security, which also reflects nonproliferation concerns. Such concerns have played a role in the choice between open and closed fuel cycles in some countries. The infrequent mentions might be because scientific articles that address security are a function of the extent to which this value can be addressed through innovation and hence requires technical and scientific research. Most of the literature on which figure 2 is based discusses technical and scientific issues and (far) less governance and policy issues, which would include security. (In contrast, safety may be relatively overrepresented in the technical literature as much research focuses on it.)

Value changes in the previous context may have an effect on nuclear reactor operations in both the short and long term. Take the increased emphasis on safety due to large nuclear accidents. In the short term, this has, in each case, led to some operational changes or smaller design changes that can be implemented in existing reactors to increase operating safety (e.g., design proposals to incrementally improve light water reactors).

The long-term effect mainly concerns the shift to passive safety and the development of new generations of nuclear reactors based on passive rather than active safety systems, as well as a shift in thinking about the governance of (global) nuclear safety (Taebi and Mayer 2017). These latter effects, however, may take quite long to be effected at the level of operational nuclear reactors as the time from the proposed development of a new reactor through its design, political and regulatory approval, construction, and actual operation is typically several decades.

Designing for Changing Values

A main upshot of this discussion is that there may be discrepancies and time lags between values that are given priority in the different contexts and at different times. This means that if new reactor designs are based on values currently deemed important in the nuclear scientific community (figure 2), there may be a mismatch with societal priorities (although there is no clear evidence of such a mismatch). Another potential problem is that by the time research and design efforts have materialized in new operating reactors, values in society and the nuclear engineering community may have changed so that the new reactors reflect past value priorities. Both issues could give rise to serious ethical problems.

How, then, to account for changing values in current nuclear reactor research and design? This is difficult, but there are at least two possibilities.

First, one can try to anticipate value change. Not all value changes are predictable, but it may be possible to detect signs of future change. One interesting hypothesis, that requires further research and testing, is that value changes may first manifest at the societal level and then, over time, affect the nuclear scientific community. If so it may be possible to develop methods to anticipate value change at the societal level.

We are exploring the possibility of finding latent values and value changes in texts with the help of topic modeling (de Wildt et al. 2018, 2020). In the same vein, one could ensure that societal value changes translate more quickly into priorities at the level of research and design of new reactors, for example by monitoring societal value changes or involving societal stakeholders in setting research priorities. This would also seem desirable for other societal as well as ethical reasons; it fits well with the idea of responsible research and innovation aimed at better aligning research and development (R&D) with the values and needs of society (European Commission 2014).

A second possibility may be to build more flexibility and adaptivity into nuclear reactor design and related R&D trajectories, so that changing values can be better accommodated. For example, modular designs (such as those discussed in Lovering and McBride) might allow the replacement of parts and subsystems, rather than the construction of entirely new systems, to deal with value change.

Another option is to deliberately allow for competing technologies and technological trajectories. While this may be costly in the short term, it increases future possibilities to adapt to changing values.

Acknowledgment

This paper was written as part of the project ValueChange, which has received funding from the European Research Council under the European Union's Horizon 2020 research and innovation program (grant agreement no. 788321). The opinions expressed are those of the authors and in no way reflect the opinion of the European Commission.

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Risk-limiting audits can accommodate different types of elections and provide statistical proof that the outcomes are valid.

Risk-Limiting Audits in Colorado Elections: A Brief Overview

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Matthew Fitzgerald

Elections are the bedrock of America's democracy. Citizens hold their government accountable by voting to elect or remove representatives and other officials and make important decisions about which policies are enacted. Elections must therefore be accurate and trustworthy. However, electoral integrity becomes more challenging to ensure as electronic voting is more widely used. Electronic voting introduces a myriad of potential ways for those who seek to sway the outcome of an election to tamper with the results.

To ensure accurate election results and protect against the risks of a cyber-attack, Colorado uses an election auditing technique called *risk-limiting audits* (RLAs). On November 7, 2017, the state conducted the first such audit in US history.

RLAs use statistically rigorous processes to confirm that reported election outcomes are correct. This article provides an overview of RLA measures, with a focus on techniques and procedures used in Colorado. It also expounds on ways this process may improve integrity safeguards, and suggests potential future research and development of RLA processes.

What Are Risk-Limiting Audits?

Since the passage of the Help America Vote Act in 2002, states have increasingly relied on electronic voting equipment in the administration of elections. However, electronic machines, which may be used either to collect electronic ballots or to scan paper ballots, introduce a host of potential vulnerabilities that threaten the integrity of election results. Faulty machines may record, store, or transmit votes improperly because of flaws in product design or lack of proper maintenance. They can also be a target of cyberattacks, as both foreign and domestic parties may seek to manipulate the vote tallies recorded by electronic voting equipment.

To combat the threat of invalid election results, whether due to errors in ballot counting, malicious cyberattacks, or other means, those interested in election security have proposed measures that may enhance the security of elections. Many of these measures involve improvements to electronic voting equipment, changes in voting procedures, or more stringent auditing of the equipment used to record or tally ballots.

RLAs focus on the actual votes cast and provide a means for election officials to audit the *result* of an election, rather than focusing on the voting process or the equipment involved. In this way RLAs help to provide assurance to voters, candidates, and other interested parties that the correct winner was chosen in a given election.

Components of Risk-Limiting Audits

RLAs can be used in a variety of election formats, but existing RLA procedures rely on paper ballots to ensure a verifiable audit and therefore cannot be used in elections in which votes are cast exclusively on digital recording equipment. Because paper ballots are the foundation of the process, it is essential to accurately maintain the paper trail. This necessitates procedures to certify its integrity.

A Ballot Manifest

Election officials must craft a ballot manifest description, detailing the way ballots are collected, the sequence in which they are stored, and the location where they are held (Branscomb 2017). A well-defined ballot manifest can help election officials ensure that errors in counting or sorting do not cause a discrepancy that impairs their ability to conduct an effective audit.

In elections in which votes are tabulated by direct-recording electronic (DRE) voting machines, files designed using the ballot manifest determine how votes are collected and tabulated. Optical scanners that tabulate paper ballots similarly use the ballot manifest to dictate how the machine reads and stores the votes on each ballot. In Colorado, statewide voting by mail necessitates that paper ballots be collected and sent to optical scanners for tabulation.

In preparation for an RLA, election officials must establish a *risk limit*. This is described by the Colorado secretary of state as “the largest statistical probability that an incorrect reported tabulation outcome is not detected and corrected” (Colorado Secretary of State 2020). As an example, if a risk limit is set at 9 percent, 91 of every 100 possible invalid election outcomes should be caught through the use of the audit.

Random Ballot Selection

To determine which ballots will be audited, a seed number is generated. A random number generator uses the seed number to calculate pseudorandom values that each correspond with a cast ballot that will be audited. There are many ways the seed number can be identified; the goal is to generate a number that is as randomized as possible.

RLAs focus on the actual votes cast and enable officials to audit the result of an election.

The randomness of the selected ballots is a vital component of the RLA. To maintain public confidence in the audit’s integrity, it must be ensured that (i) any voter’s ballot may be reviewed in the audit process and (ii) it is not possible to predict which ballots will be reviewed (so anyone seeking to undermine the election’s integrity cannot manipulate ballot order to avoid review of compromised ballots). With the ability to predict the seed number, an individual or group seeking to undermine the audit process could circumvent the audit, rendering it ineffective.

A random selection of ballots can be achieved through measures that use a physical source of randomness and the cohesive effort of multiple individuals. In Colorado, the secretary of state creates a random seed number by inviting members of the public to a meeting where they take turns rolling a 10-sided die to generate a number of at least 20 digits. This number is used to initialize a pseudorandom number generator to determine which ballots will be randomly selected for the audit (Colorado Secretary of State 2020).

Only a very small percentage of ballots may be audited. The exact number depends on the reported margin of victory in an election as well as the degree to which audited ballots have affirmed the accuracy of the election outcome.

Two Postelection Ballot Audit Methods

After polls have closed and ballots have been tabulated, the randomly selected ballots are reviewed by ballot officials. There are several ways they might be audited, two of which are ballot-polling audits and comparison audits (Lindeman and Stark 2012).

Because of the statistical methods used in an RLA, a relatively small number of ballots may satisfy the risk limit.

In a ballot-polling audit, ballots are examined after identifying the reported winner after the initial vote tabulation and comparing this initial result with the results found in the limited number of randomly selected ballots during the RLA process. This method typically requires a far greater number of ballots to be reviewed than a comparison audit. In a comparison audit, the reviewed ballots are compared to a cast vote record to confirm the accuracy of the original ballot tabulated.

With both types of audit, reviews continue until the statistical risk limit has been fulfilled or, if necessary, a full recount is completed (Lindeman and Stark 2012).

Advantages of the RLA

Software Independence

The use of electronic equipment in US elections has become commonplace. But DRE machines may report invalid results, because of either faulty programming or malicious activity. The same may be true of optical scanning equipment used in elections administered with paper ballots. In both cases, the tabulation of voters' ballots must, at some point, be entrusted to computer programmers who, despite their best efforts, cannot deliver software that is perfect in terms of either functionality or security.

The fallibility of electronic voting equipment has resulted in calls from election cybersecurity experts for the implementation of software-independent voting infrastructure (Rivest 2008). Software independence in this context does not entail the elimination of all electronic voting equipment. Instead, it embraces procedures that allow elections to proceed effectively in the absence of reliable electronic voting equipment. RLAs support software independence by creating a post-election environment in which there is an organized paper trail that can be sampled for accuracy.

Diverse Applicability

Rules governing election procedures are primarily made at the state and local levels. The result is an American electoral landscape with diverse procedures for voter registration, ballot collection, and voting equipment selection and monitoring. An advantage of the RLA is that it can apply to a variety of elections (Lutz 2019).

As long as a locality's electoral procedures meet the criteria mentioned above, it has a high probability of being able to conduct an RLA. With existing RLA software and procedures, "complicated calculations or in-house statistical expertise" (Lindeman and Stark 2012) are not required to implement a risk-limiting audit.

Efficiency

In addition to versatility of implementation, RLAs provide a level of efficiency that does not exist in more traditional election recount procedures. Because of the statistical methods used in the development of the RLA, a relatively small number of ballots may satisfy the risk limit, as indicated in the following description of a ballot-polling audit procedure (Lindeman and Stark 2012, p. 44):

> [I]n the 2008 presidential election, 13.7 million ballots were cast in California; Barack Obama was reported to have received 61.1% of the vote. A ballot-polling audit could confirm that Obama won California at 10% risk (with t = 1%) by auditing roughly 97 ballots—seven ten-thousandths of one percent of the ballots cast—if Obama really received over 61% of the votes.

A useful analogy provided by Lindeman and Stark (2012) is that of taste-testing soup. If a chef desires to know whether the soup needs more salt, she needs only to stir it thoroughly and taste a spoonful. The spoon will contain only a small volume of soup relative to the pot, but the characteristics of its contents should be indicative of the whole. Similarly, only a small number of ballots need be used for an audit, so long as the selection process is characterized by thorough randomization.

One of the reasons for this efficiency is that an RLA is not implemented to confirm the exact total of votes received by each candidate. Instead, it confirms, within a selected unit of risk, whether the outcome of an election, in terms of winners and losers, is likely to be correct. As Lindeman and Stark (2012, p. 42) comment, "Risk-limiting audits do not guarantee that the electoral outcome is right, but they have a large chance of correcting the outcome if it is wrong."

Expediency

RLAs may also prove to be much more expedient in comparison with auditing processes that confirm the functionality of electronic voting equipment (Lindeman and Stark 2012). Generally, the more complex a voting software system, the higher the chance that bugs or security gaps may be identified through conventional auditing measures and the longer such procedures may take. Simply confirming the accuracy of voting results seems to achieve the goals of such measures—making sure that the winner indeed won, and the loser truly lost—at a comparatively lower resource cost.

The use of RLA procedures provides election officials with a statistically reliable, transparent method by which they might increase voter confidence in election outcomes. Incorrect election outcomes can be identified, mitigating the potential of faulty tabulation, regardless of whether this is due to machine or human error. Confirming the accuracy of electoral outcomes may enhance and justify public trust (Hall et al. 2009).

Possible Improvements to the RLA

RLA systems remain relatively novel in practice. Only four states currently require them by law: Colorado, Nevada, Rhode Island, and Virginia (Lynch 2019). As more states consider the use of RLAs in their election processes, it may be prudent to consider how existing RLA systems may be improved.

While RLAs can be used across a variety of races on a ballot, no state has used them for all races across the entirety of the ballot. In Colorado the secretary of state is required to choose at least two statewide contests in a general election and at least one countywide contest in a primary election for an RLA. Colorado's election rules indicate criteria that the secretary of state uses when choosing which contests to audit, such as the reported margin of victory, the number of ballots cast, or any causes for concern about the accuracy of the outcome (Colorado Secretary of State 2020).

These criteria are commendable, but the audit may be improved with additional criteria. If election officials want audits to enhance the perceived legitimacy of electoral contests, they may be well advised to also consider, as recommended by Citizens' Oversight founder Ray Lutz (2019), the amount of publicly disclosed campaign funds in a political race when deciding which contests to audit. The amount of money spent on a political contest may indicate perceived competitiveness or significance, making high-dollar contests prime targets for fraud. Such contests may also be more visible and of greater interest to voters.

The RLA may increase public confidence in election outcomes (Hall et al. 2009), but because of its relative novelty there is little evidence thus far. While state laws may be written to emphasize transparency in the audit process, the statistical processes involved are unlikely to be considered easily comprehensible by the public.

The amount of money spent on a political contest may make it a prime target for fraud.

Whether public trust in the results of an audit is higher than in the software programs and algorithms used in electronic voting equipment may be worthy of future research. At a minimum, education of the electorate about the advantages of RLAs would be beneficial.

Conclusion

There is no simple approach for securing elections in the United States. With the current patchwork of state and local election regulations, the scope of threats to the election infrastructure is vast. The use of electronic equipment for collecting, storing, and tabulating votes brings with it the potential for invalid vote records due to either intentional or unintentional equipment malfunction. Paper ballot systems, although typically less susceptible to fraud, require that voters mark their ballots properly and that these marks be clearly distinguishable for those counting votes. Any new election process vetted for implementation must take into account the specific electoral environment in which it will be introduced.

RLAs may nonetheless prove to be sufficiently useful for more states to consider incorporating them in their election procedures. They provide supplemental statistical proof that election outcomes are valid, and can be implemented in a variety of ways to accommodate different types of elections.

While the extent to which RLAs increase public trust in elections is thus far unconfirmed, their potential makes them an important option to consider in democratic election best practices.

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An Interview with . . .

Don Norman (NAE), Cognitive Engineer and Author

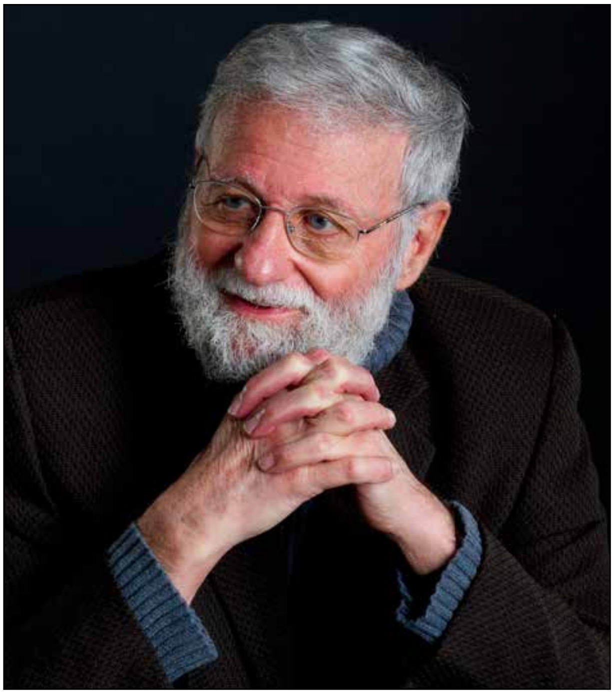

Photo by Peter Belanger.

RON LATANISION (RML): We're delighted that you're available to speak with us today, Don. You are a trained electrical engineer who went on to become the founding director of the Department of Cognitive Science and chair of the Department of Psychology at the University of California, San Diego (UCSD). That's a pretty unusual career for an engineer.

CAMERON FLETCHER (CHF): And I understand you got your PhD in mathematical psychology. Can you briefly describe what that is?

DR. NORMAN: First let me start by telling you my career history. While I appear to have made radical changes in what I'm doing in the field, in my mind it hasn't been radical at all, it has been slow, incremental changes. In many ways I'm still doing what I was trained to do as an engineer.

I graduated from MIT as an electrical engineer in 1957. I suspect I was just a middling student. Had we had a yearbook where we voted people most likely to achieve, I probably would have been voted most unlikely to succeed.

But I had gotten interested in computers. In those times MIT had analog computers and I did my thesis using them. We didn't even really understand the difference between analog and digital computers.

I took a job, I think it was at Raytheon, I'm not sure anymore, in Philadelphia, and they said, 'We'd like you to get a master's degree. Here's the application to the University of Pennsylvania and we'll cover it.' I filled out the application and a couple months later, to my great surprise, I got a letter from Penn saying they wanted to offer me a position as an assistant instructor at a salary of, I think, $7000 a year.

CHF: That was quite reasonable then.

DR. NORMAN: Yes. I did not have any plans then to go to graduate school, but I said, to myself, 'Gee, why don't I turn down Raytheon and just go to Penn?' That's what I did, and I continued my work in engineering. My specialty was circuit design.

But I really wanted to get into computers. I took an early course in programming that one professor was teaching, but that's all they had. They said, 'Stick around, in a year or two we'll probably have a computer degree and you can be the first student.' I didn't want to stick around, though, and I especially didn't want to go into a PhD program in electrical engineering.

But the Department of Psychology, which I knew nothing about, got a new chair and hired a new professor. The new chair, Bob Bush, had his PhD in physics, and the new professor, Duncan Luce, had his PhD in mathematics (and his undergraduate degree in aeronautics at MIT). Bush gave a talk and I thought, 'That sounds like what I'm interested in.' So I talked to Bush and he said, 'You don't know anything at all about psychology, wonderful.' He assigned me to work with Luce.

They were developing a field called mathematical psychology. Duncan decided I didn't know enough

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This interview took place June 9, 2020. It has been edited for length and clarity.

math, so he sent me to the math department to take a course in algebra. I had 6 years in engineering math, but that wasn't enough.

I became really interested in sensory psychology, because studying hearing and seeing and so on was really close to what I had been doing—it was really an engineering problem in many ways.

I became interested in sensory psychology, because studying hearing and seeing was really about engineering in many ways.

There was something called the neural quantum theory of hearing, which basically said that the perception of loudness was not smooth and continuous: it was made up of many small, discrete steps—it was quantal.

Think of loudness being represented by the rate at which the nerves attached to the hair cells in the inner ear fire: increase the sound intensity by a tiny amount and, ping, the nerves fires with an extra impulse. This idea had some credibility, having been studied by a number of famous people in the Harvard psychology department, such as Georg von Békésy, who eventually got a Nobel Prize for his discoveries about hearing; George Miller, one of the founders of the study of cognition in psychology; and Ulric Neisser, who coined the term *cognitive psychology*.

The ear is incredibly sensitive—it can detect Brownian motion. As I worked on my thesis, I was having really weird results. I realized that I could make sense of them if there was a decision threshold for the people listening to decide whether the sound they heard was louder or not: if the sound was above the threshold, they said, 'yes, it's louder,' otherwise they said 'no.' My breakthrough came when I realized 'What if it was probabilistic decision making, where the threshold varied during the experiment, sometimes set at a 1 quantum change and other times at a 2 quantum change?' This produced a set of weird, nonmonotonic curves of loudness as a function of intensity—which matched my data. And so that was my PhD thesis. The first person who decided to publish it was a mathematical psychologist named Dick Atkinson.[1]

I was a graduate student for only about 2 years in psychology at Penn. I almost flunked out, because most of it was memorization of people's experiments, which I thought was meaningless. At MIT I had learned you didn't have to memorize stuff, you had to understand the principles and then you derived the answer.

But for the areas in psychology where derivation was possible—like psychoacoustics, trying to understand how the ear works and so on—it was engineering. So there I shined. I actually taught some of the advanced classes in psychology while flunking out of the beginning classes.

RML: Selective application of your intellect, is that what it is?

DR. NORMAN: Yes, in fact that has carried through to today. When I was accepting graduate students, if I had applicants with straight As I didn't want them. I wanted somebody who had done more experimentation and taken a few courses they had done badly in. I took a graduate student who had flunked out of Berkeley and I had trouble convincing UCSD to let me accept him. He turned out to be one of my best graduate students. He was flunking because he was bored.

Anyway, when I was finishing my thesis Duncan said, 'Okay, where would you like to go now?' We discussed various possibilities and concluded I should go to either MIT or Harvard. He sent me to MIT and to Harvard to interview them. I visited MIT and there was some really neat stuff going on in areas I didn't know about; at Harvard it was completely different. I decided to go to Harvard because I'd learn more.

At that point George Miller and Jerry Bruner, two of the founding fathers of modern psychology, headed something called the Center for Cognitive Studies. I didn't even know what the word *cognitive* meant. But on my first day I met a few people and immediately started a big argument with them. We were talking about human memory, and I said, 'Of course there's temporary memory and longer-term memory, it's obvious.' Well, it wasn't obvious, that was in fact groundbreaking news in the psychology community.

I learned a lot and became a fan of William James (who taught at Harvard; he died in 1910). The early American psychologists like James were doing wonderful work, but

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[1] Atkinson RC. 1964. Studies in Mathematical Psychology. Stanford University Press.

it got killed by the behaviorists who didn't want to study the brain or the mind, because 'if you can't see it you can't study it, we just study what can be measured.'

At Harvard I got interested in and started experimenting in memory. I worked with Nancy Waugh—the woman I had this big argument with. (On the East Coast arguments are considered the way you work: When we argue we're developing ideas. When I got my job in California and continued in that fashion, people took me aside and told me to stop.)

So Nancy and I argued, and we published about seven or eight papers together, including one that we called "Primary Memory" (we should have called it *short-term memory*), after William James. I published that paper in my first few months as a postdoc, in the *Psychological Review*, the best journal in psychology. We did a whole bunch of experiments—in fact George Miller bought me a computer to run the laboratory, so our lab had one of the very first digital computers.

When I was at MIT I had to take a couple of courses in the so-called humanities, and one of them used George Miller's textbooks. It was a course on how people heard and remembered things, especially in noise. One of the things he pointed out was that if I'm listening to random words in noise it's very hard for me to understand them, but if they're the same words in a sentence it's much easier to understand them. That's a powerful finding. George is famous for his paper "The Magical Number Seven, Plus or Minus Two," about limitations of human memory and how it shows up in many different situations.

Also when I was at MIT I took a course by this new guy. My roommate insisted I should take this course because the guy was supposed to be pretty good. So I took the course by this new professor, his very first course and he used his thesis as the textbook. His name was Noam Chomsky.

There were two parts to the course. One was the philosophy of language and how it should be studied. The other was his formal language for describing different languages. It was a finite state grammar. At the end of the course he told the students that when he taught the course at Penn the students loved the philosophy part but were lost and didn't understand the finite state grammar; when he taught us we didn't understand the philosophical part, but thought the finite state grammar was easy.

Anyway, at Harvard they had a lunch every week with some of the top philosophers and people from the Center for Cognitive Studies. Noam Chomsky came every week. Basically everybody who was anybody moving up came through Harvard, so it was a really great education.

After a year George got me an appointment in the Psychology Department. When I was introduced to the faculty, BF Skinner, a behaviorist and the most famous psychologist in America, stood up and denounced me and my field. Welcome to Harvard.

I also started working with a guy in the MIT Psychology Department, Wayne Wickelgren. We discovered signal detection theory, which was introduced into psychology by Dave Green and John Swets (they had worked at BBN together). JCR Licklider was there; he worked for ARPA and set up a lot of the time-shared computers and the beginnings of the internet, and he was a psychologist. In fact, he had studied the neural quantum theory as well.

When I got an appointment in the Harvard Psychology Department, BF Skinner, the most famous psychologist in America, stood up and denounced me and my field.

In my work in signal detection theory I was thinking you have to get this entire receiver operating characteristic curve, and it takes a lot of work, and it's not always easy to get the whole thing. Then one day I realized I could do a lot with just one data point. That's when you ask somebody to remember something and later you show them items and ask 'Which one did I show you before?' When they select one, they can have a "hit" (they say yes to the correct object) or a "false alarm" (the object they pick isn't one I showed them). The hit and false alarm rate is what's important in detection theory. You're listening to a weak signal, but it's very noisy and sometimes the noise sounds like a signal. So you have to have a criterion, to say 'if it's above that criterion I'll say it's a signal, and if it's below I'll say it isn't.' If you make the criterion very high you won't have any false alarms—but you're also going to miss a lot. If you make it very low, you won't miss any, but you may have lots of false alarms.

RML: This sounds like something that might be relevant to today's interest in covid-19 sensors and detectors and testing. Is there any connection?

DR. NORMAN: Yes, absolutely. Detection theory is widely used. In fact, it explains why some of the tests being used today give false positive results, even though their main failing is that they give false negatives. To avoid false negatives, they adjust the threshold for decision making to a low value, which decreases the false negatives, but at the expense of an increase in false positives.

Back to my discovery. Suppose I have two different experimental conditions. I get a higher hit rate in one than in the other, but also a higher false alarm rate. How do I know whether one experimental condition is better than the other? I realized I could do a geometric, graphical diagram. With only a single data point (hit/false alarm rate) I could divide the plot of hits versus false alarms into three regions: one where any point would be superior, one where it would be inferior, and a third region that is undecided. I published that paper in *Psych Review*.[2]

> *There are fundamental principles about why people have trouble with Norman doors. There's a science behind it.*

Then I published a few other papers with some friends where we said, just take the area under that curve—it's a very simple curve, it starts at 0,0, goes through the one point you have, and then goes to 1,1—and it's a good measure of performance.

That was around 1963 or '64. About a year ago I discovered that lots of medical researchers use the area under the operating characteristic that I coinvented. I looked at the papers, and they don't cite our work. But they didn't cite anyone. So I started looking for the earliest papers and yes, there was my paper. When something is commonly used, people just take it for granted and nobody remembers where it came from.

RML: I can see, given what you've described, that your experience in electrical engineering and then in psychology and cognition all comes together. I now understand your NAE citation: you were elected "for development of design principles based on human cognition that enhance the interaction between people and technology."

In preparation for our conversation today, I watched the video "Norman Doors." It's about doors that people have trouble opening, and it's a wonderful description of the interaction between technology and human beings.

You mentioned having read Henry Petroski's interview,[3] have you met him?

DR. NORMAN: Yes, I was in his house and admired his books. But he was annoyed because he was trying to show me the bookshelves, not the books.

RML: You and Henry have the same kind of spirit, I can see that. Have you known Henry for a long time?

DR. NORMAN: I discovered his book *To Engineer Is Human*, and I think I've now read every book of his. I also read his articles in *American Scientist*. So I started corresponding with him, and one day I was going to be at Duke so I wrote and asked him if I could come visit.

By the way, I didn't do that video on Norman doors—somebody just called me up one day—but it's really good. It's what I say we should teach. First of all, it's an interesting topic, and people immediately say, 'I've had that kind of trouble with doors.' Also I give some fundamental principles about why they have trouble. It allows people to see that there's a science behind this.

RML: Let me broaden that out a little. I think everything we do as engineers should have a social purpose. Doors may not work as well as we would prefer, but they do have a purpose.

What is your thinking about autonomous vehicles—automobiles, planes, people are talking about all sorts of autonomous vehicles?

DR. NORMAN: Actually I've written a bunch of papers on that topic and I've worked with Nissan on autono-

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[2] Norman DA. 1964. A comparison of data obtained with different false-alarm rates. Psychological Review 71(3):243–46. And the area paper is Pollack I, Norman DA, Galanter E. 1964. An efficient non-parametric analysis of recognition memory experiments. Psychonomic Science 1:327–28.

[3] The Bridge 45(1):49–55 (spring 2015).

mous vehicles, and I'm on the advisory board of a Toyota research group, and we have a grant from Ford Motor Company to look at autonomous vehicles. But before I get to that, I want to close my Harvard experience.

I left Harvard and was offered a job at UCSD with Dave Green, who did a lot of work in signal detection theory. We started a lab and I got really interested in human attention, studying how people were able to listen to one voice out of many, or if they fail to hear something else, what's happening, and so on. From there I got interested in the errors that people make, human error—not speech errors but errors of action.

Two computers—a Digital Equipment Corporation PDP-9 and a PDP-15—in the UC San Diego Psych Lab of Peter Lindsay, Don Norman, and Dave Rumelhart in the early 1970s. Graduate students are shown working with acoustically isolated chambers on the left where the experiments could be done free of distraction from the noise of the lab.

I partnered with two other newly hired faculty: Peter Lindsay and David Rumelhart, so we called ourselves "the LNR Lab." And of course we bought computers to control our experiments. At Harvard we had a Digital Equipment Corporation PDP-4. At UCSD, we started with a PDP-9, then a PDP-15, and finally a VAX.

I asked my students and everybody I knew if they made an error—say, flipping the wrong switch, or going to work on a holiday—to write down what error they made and how they detected it. I collected these errors and sorted them and came up with a descriptive categorization of them, along with a theoretical framework. And again I published a paper in *Psych Review*.[4]

I started the paper by saying, 'One day one of my colleagues told me he must be getting old, he was making errors. He said, he went to the liquor cabinet to pour himself a drink, took out a bottle of scotch and a glass, poured some scotch into the glass—and then put the glass back into the cabinet and walked off holding the bottle. I said, "I don't think you're getting old, I do that myself."' That's how I started the article, and I sent it off to the journal editor, Bill Estes, another mathematical psychologist. About a day later the paper was rejected, and the rejection letter was "Come on, Don."

CHF: That's all he wrote?

DR. NORMAN: That's all he wrote. I took out that anecdote, sent it back, and it got accepted with zero revisions.

I have another story like that, too. I wrote a paper on human attention; the theory was that when you attended to the words one person was saying, you could not attend to what anyone else was saying. Lots of studies showed you had no memory for what others said (what we called the *unattended channel*). I showed that this was wrong: there was a short-term memory for the unattended words, but you could show this only if you tested immediately after they had been spoken. I demonstrated that there was a short-term memory for unattended material.

In my paper, I said that although all the existing theories of attention (including my own) had difficulties with this result, I showed how each one could be modified to accommodate the results.

I sent it off to the *Quarterly Journal of Experimental Psychology*, the best British journal at the time, and it

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[4] Norman DA. 1981. Categorization of action slips. Psychological Review 88(1):1–15.

got rejected. They said the conclusion was weak. So I rewrote it and said the result demonstrates that everybody's theory is completely wrong except mine, because here's how my theory accommodates the results. And they said, 'Good. Thank you.' I thought that was one of the stupidest things. I was trying to be fair to everybody else and they rejected the paper.

Anyway, I was studying error and attention and all these things because they're closely related, when the Three Mile Island accident happened. I was called in by the Nuclear Regulatory Commission to look at why the operators made such stupid errors. The committee was wonderful, with a number of human factors people.

We said the operators were really intelligent and did a very good job, they made the best decisions they could have made given the information. But if you wanted to cause errors you could not have designed a better control panel than they had at Three Mile Island. It was a design problem. And that made me realize that my background in engineering and psychology was perfect for trying to understand how design works.

If you wanted to cause errors you could not have designed a better control panel than they had at Three Mile Island.

RML: What's an example of the design errors that were so apparent in Three Mile Island?

DR. NORMAN: There were roughly 4000 controls and switches in a nuclear control panel. Engineers would simply figure out what needed to be controlled and what needed to be displayed, take their straight edges, and lay out all the switches in nice long rows and all the displays in nice long rows, in vertical columns and horizontal columns.

Plants are usually built in pairs, so there are two reactors and two control panels. One of the worst design errors was a plant with two control rooms, one for each reactor. But to simplify the wiring, they made the two control rooms mirror images of each other. So an operator trained on one control room would make errors in the other control room, even though the plants were otherwise identical.

When you have a row of identical looking switches and meters, how do you know which is which? Flipping the wrong switch is easy. Operators knew they could get confused. In one power plant with five or six big switches in a row that looked the same but were critically important, we saw that the operators replaced the switch handles with different brands of beer-tap handles so they could see which was which.

RML: Did the design of the control panel materially affect the response at Three Mile Island when the events occurred?

DR. NORMAN: Absolutely.

RML: Have there been changes in the design of the control panels for nuclear plants, or for example in the cockpit of an airliner, which has a similar distribution of switches?

DR. NORMAN: We don't really know. The answer is probably yes, but there hasn't been a nuclear power plant put into operation in the United States since that time.

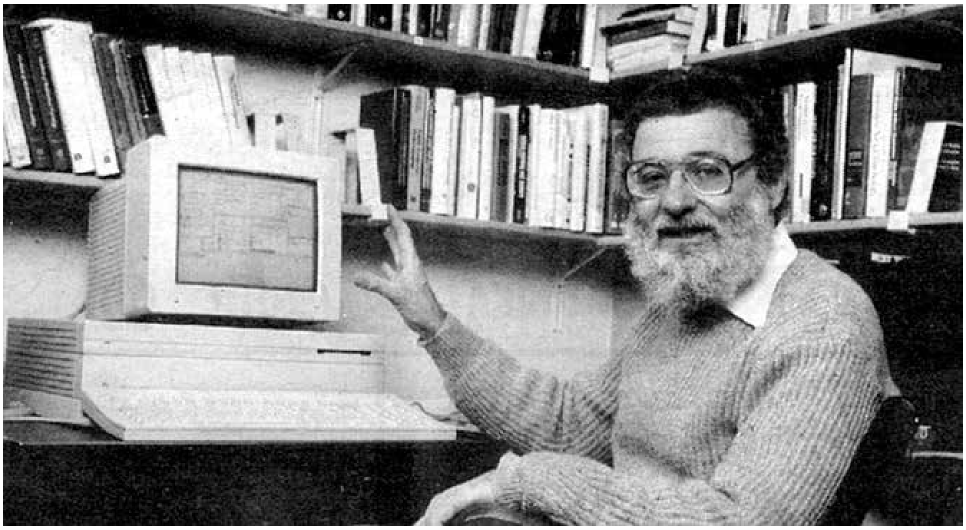
It's not the same in aviation. Aviation is actually the next step toward autonomous automobiles. In the 1940s, during the Second World War, there was a huge amount of human factors research. One of the common errors was landing an airplane with the landing gear up. The problem was that there were identical looking switches. If you wanted the flaps down, you pushed the button down. If you want the landing gear down, you pushed the switch next to it down. Quite often –

RML: They pushed the wrong thing.

DR. NORMAN: So they changed the switches so you could feel the difference: The flaps switch was a flat plane that felt like the flaps, and the landing gear switch had a wheel at the end of it.

Also in organizing the patterns of the switches they looked at what information a pilot needs to fly the plane and how a person would look at the gauges to figure out the state of the plane. In commercial aviation, the gauges and displays are organized to make it easy for the pilots to scan them quickly and efficiently. Today, commercial aviation is incredibly safe. The field of human factors (now called *human-systems integration*; NAE Section 8) has numerous, well-documented design principles, none of which went into the nuclear power systems. Every new field rejects the principles learned from other fields, saying 'oh no, we are different.' Well, these are principles about human beings, and so they apply to any field where people are involved.

CHF: Since you mention other fields, what kinds of differences have you seen in the adaptation of certain technological fields and designs as opposed to others? For example, what fields are more advanced in accommodating human factor design?


Don Norman with his Apple II computer.

DR. NORMAN: I'm going to start with the most elementary, which is personal workspaces. Let's start with the kitchen. In the kitchen you put stuff in places (1) that you can remember and (2) where you're going to need it. You don't put all the knives in one drawer, you put them depending on what you're going to use them for. There might be a knife stand for the big knives for doing major cutting and chopping, and you'll also have kitchen knives, other types of knives, and knives used for silverware. Same with pots and pans—you have a place for them, but with particular ones that you use frequently, you might leave them out. So the space is designed to fit your work style.

And everybody's kitchen is different. If you go to somebody else's kitchen to cook for them, you'll probably have a difficult time because you can't find anything because their layout doesn't match your pattern of work.

I look at a lot of craftspeople's workspaces and at the kind of tools they use and where they place them. There's a nice anthropological study of how a blacksmith organizes the tools. At the end of the day when the blacksmith cleans up to go home, they carefully arrange a bunch of tools on the floor next to the hearth, because that's where they want them. When they're heating up something they want to just reach over and get the hammer, for example.

We follow that same philosophy as we look at other designs. The place that has made the most advances is aviation. They didn't believe in human factors science at first, but the pilots would complain about where things were, so the industry developed a really good philosophy of designing, especially in commercial aviation.

The other field is computers. When the first computers came out, like the first one I programmed, the Remington Rand UNIVAC, it wasn't designed to be used, it wasn't useful at all, it was really crazy. But home computers, which were understandable and usable, became critically important.

RML: While we're on the subject of computers and electronics, I think that if people had looked differently at the evolution of the internet, maybe we would find ourselves in a different position today. Is there anything you would have done differently in rolling out the internet so that it serves the purpose that was intended—mainly as an information platform? Today it is used and abused in so many ways.

DR. NORMAN: That's a good question, and I will answer it. Let me finish on automation and then I'll get to the internet.

When the Macintosh came out, I said, 'Finally a computer that works the way we think.' I brought some of the Macintosh people in to talk about how they had done it, and I discovered some of them had been my students. That got me interested in what was going on in the computer industry, which is eventually why I retired and went off to Apple. Today, computer science understands the importance of designing for people; the specialization is called *human-computer interaction* (NAE Section 5). I think separating this one area into two sections weakens their impact: we ought to have a new NAE section on human-systems integration. I happen to be a member of both sections 5 and 8, but that is rare. All of us ought to be together.

> *The most dangerous part of automation is when it's almost automated.*

Back to automation. We've known for years that if you're doing a task where nothing happens for hours and hours, you can't pay attention. I was studying human error, working with NASA Ames in Silicon Valley, they're the world experts on aviation safety. I was applying my understanding to aviation, and that's where I learned a lot about accidents and about how one should design for people. I developed a lot of the ideas there and eventually coedited a book, *User Centered System Design*,[5] about that and what was going on in the early home computers. That was the first use of the term *user centered* and also brought out the importance of designing for the system.

In a paper about 30 years ago I said the most dangerous part of automation is when it's *almost* automated, because if it's still manual you have to pay a lot of attention, and if it's completely automated you don't have to pay any attention.[6]

But when it's almost automated, it's really dangerous, because when something works perfectly for hours and hours, people simply cannot stay alert. They lose what we call *situational awareness*. Then when something unexpected happens and the automation cannot cope, it can take a long time for people to regain situational awareness and take over properly.

In aviation when pilots are flying along and suddenly the plane starts diving, the first thing they do is say, 'Oh shit,' and then they say, 'What's going on?' But if the plane is at an altitude of 30,000–40,000 ft. they have several minutes to figure it out. Commercial aviation pilots are well trained, so most of the time they save the plane.

So now we have automation in the automobile. The problem is that people are beginning to trust the automation: overtrust. Tesla drivers provide a good example. There have been a number of deaths in Tesla autos because the better the automation, the less people will pay attention.

In an automobile drivers are not well trained. Moreover, when the automation fails, the response must be made in a fraction of a second.. At 60 miles an hour, in 1 second you've gone 90 feet. Data show that it takes 10–20 seconds for people to figure out what's going on and make the right response. That means they've gone 1000–2000 feet. Too late.

I'm actually a big fan of automation, because I think driving is dangerous. Instead of 40,000 deaths a year in the United States and 1 million in the world, automation might reduce this by 90 percent. That's still 4000 deaths a year in the United States, but it is a dramatic improvement. I'm not a fan of partial automation, though. And I don't like ASME's five levels of automation, because it misses all the subtleties.

You asked me about other problems with technology. One of them is the inability to predict exactly how any technology that is adopted by hundreds of millions of people will be used. The internet is a good example of a wonderful invention that has evolved into a powerful vehicle that nobody in their wildest dreams anticipated.

I lived through the early days of the internet (when it was called the ARPAnet). I'm friends with a lot of the people who did the early design. A major problem today is the lack of security, in part because the underlying infrastructure doesn't readily support security. Why? Because it was designed for a bunch of people trying to connect their computers so they could share the computer power.

Once, in the early days, a student at UCSD broke into somebody else's computer and did some damage. There was a big fuss. People kept asking, 'What should we do?' Nobody said, 'Let's redesign the system.' I talked to the student, and I said, 'We don't do that.' And he stopped. In those days everybody trusted everybody.

In hindsight, of course we should have done things differently. But at the time it was a bunch of collaborative people, nobody realized it was going to take over the world. So there was no security built in, none whatsoever, and in many ways that was deliberate. Trying to add it afterward is almost impossible.

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[5] Norman DA, Draper SW, eds. 1986. User Centered System Design: New Perspectives on Human-Computer Interaction. Hillsdale NJ: Lawrence Erlbaum.

[6] Norman DA. 1990. The "problem" of automation: Inappropriate feedback and interaction, not "over-automation." Philosophical Transactions of the Royal Society B 327(1241):585–93.

Besides, it was restricted, you could only use it if you had a DARPA contract, if you worked for government. I remember some company sent out a big advertisement across the internet advertising their product, and wow, they were banned, they were told 'Get off, you're not allowed to use this.' We could not imagine that this network could be used for advertising. When the system was designed, we could not imagine sending speech over the connections. Video? No way. Deliberate sabotage? Criminals? Malware? Fake news. And if you can't imagine something, you can't design a system to protect against it. Want another example of the inability to predict? Think of automobiles. They were going to reduce pollution in cities, which were covered with horseshit. Nobody predicted that automobile exhaust would be a far worse form of pollution. Who could have predicted there would be billions of automobiles?

RML: My thought is that if we leave it to scientists and technologists to develop systems, without involving let's say social scientists, people with an understanding of human factors and so on, are we not missing an opportunity to think more deeply about how technology interacts with people? When we're developing engineering systems, and our goal is always to serve society, to make sure that the system serves a social purpose, should we not bring social science into that conversation?

DR. NORMAN: Yes, absolutely. I've been making that point to the deans of engineering schools. Why do we do engineering? It's usually for society and people. So we need to bring these courses into engineering. Engineers should understand these factors, absolutely. But it's difficult to change engineering culture, because the thinking is 'we don't have room for more courses.' I'm saying it shouldn't be a different course, it should be taught in existing courses.

Northwestern University's School of Engineering now requires all engineering students to take a design class as freshmen. For two thirds of the year they do a design exercise for people—they go off to the local hospital system and design things to help patients. This is wonderful. I give great credit to the dean, Julio Ottino (NAE).

Nonetheless it is wrong to say 'we should always think of the societal consequences.' Yes, we should, but we will almost invariably fail. We couldn't have predicted the problems with the internet or the problems of pollution. Herb Simon, a Nobel laureate who was a friend of mine, had this wonderful statement: 'It's easy to predict the future, people do it all the time. The hard part is getting it right.'

I know I didn't predict what would happen with the internet, that it would change everybody's life. Nobody did, except maybe a few science fiction writers. They're often the best predictors.

CHF: So much of innovation is caught up with unpredicted, unintended consequences.

DR. NORMAN: That's right, because the technology changes human behavior so that suddenly people are behaving in ways we never would have expected.

CHF: Now that would be a fascinating topic for you to explore, Don—the impact of technology on human behavior in the long term. Not necessarily right now, though, because we've run out of time.

RML: Don, thank you very much.

CHF: Yes, this was so interesting.

DR. NORMAN: Great, thank you very much.

NAE News and Notes

NAE Newsmakers

Karl Deisseroth, D.H. Chen Professor of Bioengineering and of Psychiatry and Behavioral Sciences, Stanford University, has been awarded the **2020 Dr. A.H. Heineken Prize for Medicine** by the Royal Netherlands Academy of Arts and Sciences. He received the prize for developing both optogenetics, a method to influence the activity of nerve cells with light, and hydrogel-tissue chemistry, which enables researchers to make biological tissue accessible to light and molecular probes. Both discoveries play an important role in current brain research. The Heineken Prizes are the Netherlands' most prestigious international science prizes.

Syracuse University has announced Chancellor's Citations for Excellence as part of the 2020 One University Awards. **Charles T. Driscoll Jr.**, Distinguished Professor and University Professor, Department of Civil and Environmental Engineering, received the **Lifetime Achievement Award** for his extraordinary record of more than 40 years of contributions to the university's core mission, as a researcher and teacher-mentor to both undergraduate and graduate students.

Samyang Biopharm USA, Inc. has established the **Samyang CRS Award in Honor of Sung Wan Kim**. Dr. Kim, who died February 24, was distinguished professor of pharmaceutics and pharmaceutical chemistry and bioengineering, Department of Pharmaceutics and Pharmaceutical Chemistry, University of Utah. The new award was announced at the 2020 annual meeting of the Controlled Release Society (CRS); the inaugural award will be presented at the 2021 conference and annually thereafter to a midcareer scientist in biomedical research who is emerging as a leader in drug discovery.

Ross E. McKinney, professor emeritus, University of Kansas, has been honored with an endowed professorship in his name. Dr. McKinney developed and directed the university's environmental engineering program during his tenure of more than three decades and is regarded as a legend in environmental engineering. His research focused on the biological treatment method for industrial and municipal wastewater treatment and led to his being named by international technical journals the "Father of Activated Sludge." The endowment will cover a salary supplement and discretionary funds for a full professor in environmental engineering, and the position's focus is intended to be on water quality.

Ellen Ochoa was cited as one of 100 Women of the Century posted by *USA Today*. She was the world's first Hispanic female astronaut (1990), the first Latina to travel to space (1992), and the first Hispanic to be named director of NASA's Johnson Space Center (2013–18).

Eva Tardos, Jacob Gould Schurman Professor of Computer Science, Cornell University, has been **elected to the American Philosophical Society**, the oldest learned society in the United States.

Alejandro Miguel San Martín, chief engineer, guidance, navigation and control, NASA/Jet Propulsion Laboratory, is the recipient of the **2020 Yvonne C. Brill Lecture in Aerospace Engineering.** The lectureship was established in 2013 in memory of Yvonne Brill, pioneering rocket scientist, AIAA honorary fellow, and NAE member. The lecture features distinguished leaders who speak on how contributions in aerospace research and/or engineering influence, support, or enable a diverse and robust engineering community. This year the topic will be "From Airbags to Wheels: The Evolution of GN&C for Entry, Descent, and Landing." The lecture will take place October 7 in conjunction with the virtual NAE annual meeting.

Chien-Fu Jeff Wu, Coca-Cola Chair in Engineering Statistics, Georgia Institute of Technology, was chosen to receive Georgia Tech's highest faculty award, the **Class of 1934 Distinguished Professor Award**. Dr. Wu is considered a visionary in engineering statistics. The award recognizes outstanding achievement in teaching, research, and service.

Ajit P. Yoganathan, Wallace H. Coulter Distinguished Faculty Chair and Regents' Professor, Coulter Department of Biomedical Engineering, Georgia Institute of Technology, has become **the first honorary fellow of the American Association for Thoracic Surgery**. He is recognized for inventing the science of prosthetic heart valve engineering and planning software for difficult cardiac surgeries in babies with deadly birth defects. The award recognizes persons who are not cardiothoracic surgeons but have made important contributions to the fields of cardiac or thoracic surgery.

IEEE has announced the winners of its 2020 medals and field awards. Because of the covid-19 pandemic the honors ceremony was canceled and recipients are being recognized online (https://ieee-vics.org/). Awardees follow in alphabetical order. **P. Daniel Dapkus**, William M. Keck Distinguished Chair of Engineering, Ming Hsieh Department of Electrical Engineering, University of Southern California, was awarded the **Jun-Ichi Nishizawa Medal** for "the development of metal organic chemical vapor deposition and quantum well lasers."

Cynthia Dwork, Gordon McKay Professor of Computer Science, John A. Paulson School of Engineering, Harvard University, received the **Richard W. Hamming Medal** for "foundational work in privacy, cryptography, and distributed computing, and for leadership in developing differential privacy."

The **Biomedical Engineering Award** was given to **F. Stuart Foster**, professor, Sunnybrook Research Institute, University of Toronto, for "contributions to the field of high-resolution imaging."

Chenming Hu, TSMC Distinguished Professor Emeritus, Department of EECS, University of California, Berkeley, received the **Medal of Honor**, "For a distinguished career of developing and putting into practice semiconductor models, particularly 3-D device structures, that have helped keep Moore's Law going over many decades."

Evelyn L. Hu, Tarr-Coyne Professor of Applied Physics and Electrical Engineering, John A. Paulson School of Engineering and Applied Science, Harvard University, was awarded the **Andrew S. Grove Award** for "pioneering contributions to microelectronics fabrication technologies for nanoscale and photonic devices."

Mark S. Humayun, Cornelius J. Pings Chair in Biomedical Sciences and Integrative Anatomical Sciences, and director, Ginsberg Institute for Biomedical Therapeutics, University of Southern California, was awarded the **Medal for Innovations in Healthcare Technology** for "contributions to the treatment of retinal neurodegenerative diseases through the use of prosthetic devices."

The **James H. Mulligan, Jr. Education Medal** was given to **Leah H. Jamieson**, Ransburg Distinguished Professor, Electrical and Computer Engineering, and John A. Edwardson Dean Emerita of Engineering, Purdue University, for "contributions to the promotion, innovation, and inclusivity of engineering education."

Michael I. Jordan, Pehong Chen Distinguished Professor, University of California, Berkeley, received the **John von Neumann Medal** for "contributions to machine learning and data science."

Nancy G. Leveson, professor of aeronautics and astronautics, Massachusetts Institute of Technology, was awarded the **Medal for Environmental and Safety Technologies** for "contributions to software safety and for the development of system safety modeling."

NAE Covid-19 Call for Engineering Action

While the world awaits a vaccine to prevent covid-19 infection, international and multigenerational teams of engineers are participating in the NAE's Covid-19 Call for Engineering Action to find creative solutions to problems caused by the pandemic. Their ideas aim to prevent the spread of the virus, help people most at risk, and make life easier under social distancing protocols.

The NAE launched the Call for Engineering Action in April to promote the brainstorming of ideas that could protect public health and the economy during the pandemic. Some 570 teams have responded to the call—university students enrolled in NAE Grand Challenges Scholars Programs, midcareer professionals, and seasoned engineers and other experts in the private sector, government, and academia.

The NAE has hosted two "pitch" showcases for particularly promising ideas; more sessions will be scheduled in the coming months. Selected teams get guidance from an Expert Review Committee to work toward bringing their covid-19 solutions to the public.

The initiative is free to join and open to anyone passionate about using engineering to address covid-19. Those interested are invited to sign up at www.nae.edu/covid19.

New NAE Committee on Racial Justice and Equity

The NAE has established a standing Committee on Racial Justice and Equity, chaired by **Percy Pierre.** The committee members are **Wanda Austin, Thomas Bostick, Nick Donofrio, Wesley Harris, Gary May, Warren (Pete) Miller, Roderic Pettigrew, Darryll Pines, Wanda Sigur,** and **John Brooks Slaughter.**

The committee will provide advice and recommendations for the NAE president and the committee chair to present to the NAE Council for action. Proposed initiatives should be consistent with the NAE's mission and aim to advance racial justice and equity. The committee may, for example,

- Recommend ways to make NAE members and the general engineering community aware of racial injustice and inequity.
- Recommend initiatives designed to increase the percentage of engineering BS and PhD degrees achieved by African Americans.
- Recommend ways that technology can be used to improve racial justice.
- Develop strategies to increase the number of underrepresented minorities in the highest leadership positions of the NAE.
- Develop strategies for fundraising to achieve the committee's recommendations.

The committee will meet three times a year, once in person at the annual meeting (beginning in 2021) and twice virtually. The members had their first meeting August 31.

New Academies Study on Next-Generation Nuclear Power Technologies

As discussed in the articles in this issue, nuclear reactors provide carbon-free energy, and advanced nuclear technologies could play an important role in moving the United States toward a zero-carbon future. Next-generation nuclear reactors can be smaller, safer, less expensive to build, and better integrated with the modern grid. However, the technical, economic, and regulatory outlook for these technologies remains uncertain.

A recently established Academies consensus study, *Laying the Foundation for New and Advanced Nuclear Reactors in the United States*, will assess the future of new and advanced nuclear reactor technologies and identify opportunities and barriers to commercialization. Following are some of the topics the study will examine:

- The operational characteristics, including safety, of these technologies and their interaction with electricity systems and other low-carbon generation resources that account for a growing fraction of electricity production
- Economic and regulatory challenges associated with commercialization
- The role, if any, of US leadership in new and advanced nuclear technologies as they relate to international nuclear energy cooperation agreements, exports, and nonproliferation
- The viability of these technologies in applications outside the electricity sector, for example in desalination, water and wastewater treatment, hydrogen production, or process heat
- The future workforce and educational needs to support the research, development, and deployment of these technologies.

James J. Truchard, who believes nuclear technology could help provide carbon-free energy more quickly and effectively than other sources, generously committed $2 million to the National Academies of Sciences, Engineering, and Medicine to support this study.

GRP and the NAE: Natural Partners in the Gulf

Born out of the 2010 *Deepwater Horizon* tragedy, the Gulf Research Program (GRP) of the National Academies of Sciences, Engineering, and Medicine uses science, engineering, and medical knowledge to work toward a safer, more resilient, and sustainable future for the Gulf. GRP activities are conducted in five program areas: offshore energy safety; environmental protection and stewardship; Gulf health and resilience; Gulf education and engagement; and data, data products, and knowledge. A new GRP strategic plan will guide activities over the next 5 years with the goal of achieving measurable change in the Gulf.

NAE President **John Anderson** has taken a keen interest in the GRP's work with the energy sector, pledging to help raise awareness of GRP activities in that area. One such activity is an Offshore Situation Room (originally scheduled for March 2020 but postponed), using interactive games to help stakeholders examine potential gaps in readiness for an offshore disaster. Three NAE members of GRP's Division Committee also bring expertise in this realm: Vice Chair **David E. Daniel,** University of Texas at Dallas (emeritus); **R. Lyn Arscott,** International Association of Oil and Gas Producers (retired); and **Thomas P. Bostick,** Bostick Global Strategies.

GRP looks forward to effective collaboration with the NAE well into the future. More information about the program is available at https://www.nationalacademies.org/gulf/gulf-research-program.

Guru Madhavan Receives ASEE Award

The ASEE Technological and Engineering Literacy/Philosophy of Engineering Division Meritorious Award has been given to Guru Madhavan, director of NAE Programs and Norman R. Augustine Senior Scholar. The award recognizes an individual or organization for promoting technological and engineering literacy/philosophy of engineering (TELPhE) through significant contribution to editorial content; outstanding service on a local, national, or international committee that promotes TELPhE; exemplary contribution to the development or promotion of TELPhE; and/or repeated delivery or development of TELPhE education in K–12, graduate, postgraduate, public service, or STEM areas. The award was presented June 24 during the ASEE 2020 virtual conference.

Guru Madhavan

Kent Thomas (NAE '16) Leaves Estate Gift to Carry on His Legacy

The NAE received a $100,000 gift to establish the Dr. L. Kent Thomas Advance, Innovate, and Mentor (AIM) Fund, made possible in part by a charitable donation from Dr. Thomas's estate to carry on his legacy. The AIM Fund will provide critical funding to NAE programs, such as the new Inclusive, Diverse Engineering for All (IDEA) Program, which will provide practical foundations and inspire community activity to broaden inclusion and diversity as well as equitable and entrepreneurial talent development.

"The AIM Fund is not only a way to continue my dad's legacy, but it is also hope for the next generation and a means to prove that if you possess the passion and the patience to educate yourself in your area of interest, you can achieve anything you wish. My dad mentored students and colleagues throughout his career from different cultures and backgrounds, with many of them becoming lifelong friends.

Kent Thomas

He would be so proud to know that this contribution will allow others to do the same," says daughter Jana Thomas-Roach.

Kent Thomas, who died May 6 at age 80, was always searching for a way to do things better and smarter. As a leader, he challenged his team to seek solutions to problems that seemingly could not be solved, and then shared the solutions with other professionals in the industry. Kayleen Thomas, Kent's widow, notes that "even though Kent was a world-renowned engineer and a top expert in subsurface flow modeling, he was very modest. He delighted in helping others make the most of their talents. He had a way of rolling up his sleeves and collaborating with his employees to develop new ideas and solve complex problems. Kent was a great conversationalist and an eager listener."

If you would like to contribute to the Dr. L. Kent Thomas AIM Fund or learn about naming your own endowed fund, please contact Lauren Bartolozzi, associate director of development: LBartolozzi@nae.edu | 202.334.3258.

Calendar of Meetings and Events

June 19	Standards of Ethics for R&D, Infrastructures, and Systems During a Crisis [webinar]
June 24	Ethics of Challenge Studies, Avalanche Testing, and Other Approaches to Vaccine Development [webinar]
June 26	Social (In)justice, Disparities in Covid-19 Health Care Delivery [webinar]
August 6	2nd NAE Covid-19 Call for Engineering Action: Concept Pitch Event
August 21	NAE FOCUS-*Bridge* Aeronautics Webinar
August 31	NAE Standing Committee on Racial Justice and Equity Meeting
September 15	2020 US FOE Preview Event
October 1	NAE Council Meeting
October 2–3	Peer Committee Meetings
October 4–7	**NAE Annual Meeting**
October 6	EngineerGirl Steering Committee Meeting

All meetings are being held virtually.

In Memoriam

ALLAN J. ACOSTA, 95, Richard L. and Dorothy M. Hayman Professor Emeritus of Mechanical Engineering, California Institute of Technology, died May 18, 2020. Dr. Acosta was elected in 1995 for contributions to the understanding of turbomachinery, particularly cavitation and rotordynamics.

WILLIAM G. AGNEW, 94, retired director of programs and plans, General Motors Research Laboratories, died May 30, 2020. Dr. Agnew was elected in 1974 for contributions to engine combustion research and the development of alternative power plants for automobiles.

FRANCES E. ALLEN, 88, IBM Fellow Emerita, IBM Thomas J. Watson Research Center, died August 4, 2020. Dr. Allen was elected in 1987 for pioneering contributions to the development of the science of optimizing compilers, and for reducing this science to practice.

BETSY ANCKER-JOHNSON, 93, retired vice president, General Motors Corporation, died July 2, 2020. Dr. Ancker-Johnson was elected in 1975 for management of engineering and scientific efforts focused on human needs.

BACHARUDDIN J. HABIBIE, 83, chair, board of trustees, the Habibie Center, died September 11, 2019. Dr. Habibie was elected a foreign member in 1986 for meritorious contributions to aircraft structural theory and design, and for creative leadership in advancing Indonesia's technological capacity and growth.

JAMES R. JOHNSON, 96, retired executive scientist, Minnesota Mining & Manufacturing Company, died October 18, 2019. Dr. Johnson was elected in 1972 for contributions to ceramics research and technology relating to nuclear fuel materials and to control of exhaust emissions.

ROBERT M. KOERNER, 85, Harry L. Bowman Professor of Civil Engineering Emeritus, Drexel University, died December 1, 2019. Dr. Koerner was elected in 1998 for the design and use of geosynthetics in the constructed environment.

THOMAS A. LIPO, 82, research professor, Florida State University, died May 8, 2020. Dr. Lipo was elected in 2008 for contributions to the design and development of variable-speed drives and motor controls.

J. DAVID LOWELL, 92, owner, Lowell Mineral Exploration, died May 5, 2020. Mr. Lowell was elected in 1999 for demonstrating relationships among geologic systems, metallogenic provinces, and hidden ore deposits.

JAMES D. MEINDL, 87, professor emeritus, School of Electrical and Computer Engineering, Georgia Institute of Technology, died June 7, 2020. Dr. Meindl was elected in 1978 for conceiving medical instruments requiring custom integrated circuits and for contributions to research, development, and education in solid-state electronics.

VALERIAN I. TATARSKII, 90, Radio Hydro Physics LLC, died April 19, 2020. Professor Tatarskii was elected in 1994 for contributions to the understanding of the propagation and scattering of electromagnetic and acoustic waves in the atmosphere and oceans.

L. KENT THOMAS, 80, consultant and Reservoir Engineering Fellow, Upstream Technology, died May 6, 2020. Dr. Thomas was elected in 2016 for contributions to the development and application of reservoirs.

Invisible Bridges

Do-It-Yourself Pandemic Models

Guru Madhavan is the Norman R. Augustine Senior Scholar and director of NAE programs.

The responsibility of building scientific models has much in common with the responsibility of sitting in the exit row on an airplane. One can enjoy the extra leg room of creating imaginative models, but it comes with a price—being "willing and able" to fulfill lifesaving duties. Modelers know well about *GIGO*: garbage in, garbage out. Now we need *AIAO*: accountability in, accountability out.

The covid-19 pandemic has resulted in a buffet of epidemiological models, all you can consume. Some models predicting the spread of the disease are feats of statistical tuning and curve-fitting—data from one context redeployed for extrapolation elsewhere. More mechanistic models use a century-old compartment approach—categorizing people as susceptible, infected, or recovered—to track the moods and modulations of the marauding microbe. Other models are occupied with producing visually top-notch outputs; however, in a pandemic, duty must come first, and beauty next.

Whatever their form, current pandemic models possess various worrisome features—chiefly, how they are promoted and proliferated without proper reflection about their quality, efficacy, and reliability, and with low or no accountability. As we use models to guide policies for covid-19, we should also use covid-19 to stimulate thinking about setting better standards for models. Lessons from real-world engineering can help.

Covid-19 has many political faces: knowledge about the virus origin seems political, the interventions are political, and the consequences are certainly political and deadly. Practical engineering also has political dimensions. Nonetheless, the code of ethics from the National Society of Professional Engineers prescribes that engineers shall "acknowledge their errors" and "advise their clients or employers when they believe a project will not be successful."

Quality, certification, licensure, training, retraining, and failure analyses are routine protocols in the pursuit of skilled accountability. Could some of these engineering standards of practice be brought to bear for disease modeling and policy advice?

Portraits of Accountability

Let's consider three forms of accountability, from an engineering perspective, that could help professionalize modeling standards.

Call the first one *effects accountability*. Most models often start and end with their intents. What goals should they achieve, under what circumstances, and with what costs and sacrifices? The wider consequences of those models are all too often ignored.

In a military context, consider when an air strike against an enemy headquarters hits a school or hospital or place of prayer instead. Unexpected civilian casualties, and the broader effects of those damages, need to be accounted for. "If the model only supports the evaluation of how often the air strike misses the headquarters, it is not sufficient in support of planning and training procedures," wrote systems engineer Andreas Tolk and colleagues in an analysis of such a scenario.[1] "Unintended outcomes, side effects, and follow-on effects are normally not modeled. This is not sufficient." That's the prime shortcoming of intent-based models, and that's why we need more models that are effects-based.

Imagine a clinician prescribing a medication without considering possible side effects such as interaction with other drugs. The notion of iatrogenesis—healing turn-

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Inspired by the name of this quarterly, this column reflects on the practices and uses of engineering and its influences as a cultural enterprise.

[1] Tolk A, Bowen R, Hester P. 2008. Using agent technology to move from intention-based to effect-based models. 2008 Winter Simulation Conference, Miami FL, p. 865.

ing into unintentional harm—becomes relevant here. Nearly 5 percent of hospitalized patients in the United States, and even more outpatients, experience some adverse event with prescribed medications, at huge costs to society—approaching a trillion dollars as long ago as 2006.[2] Medical decision models often don't take the social costs of adverse drug impacts into account, but they ought to.

The point here is that effects accountability doesn't mean legal liability, just as iatrogenesis doesn't equate to gross negligence or malpractice. Effects accountability is above finger-pointing. It's about collective safety and cumulative learning. If medical care that focuses only on intents and not on effects can have substantial social costs, then so can infectious disease models. Models frequently serve as policy medications, but we take them without necessary testing and warning labels.

Second is *explanation accountability*, which places a premium on the cogency and usefulness of insights. In complex systems such as pandemics, an individual model is inevitably weaker, whereas ensembles bolster robustness. Consider a "model of models" built by teams at the National Institute of Standards and Technology to investigate why the World Trade Center collapsed during the 9/11 terrorist attacks. Between 2002 and 2005, engineers and analysts blended information from physical model testing, burn experiments, lab studies, statistical processing, and a plethora of visual evidence. Published in eight volumes over 10,000 pages, the analyses reported on aircraft impact, building and fire codes, structural steel failure, fire protection systems, heat release patterns, emergency responses, and people's behavior.[3]

The circumstances of the investigation were daunting: the original conditions of failure could not be reproduced in simulated test conditions. Instead, the investigators built a daisy chain of approximate models, which linked to one another yet could be separated for testing. The 9/11 disaster was one of the most photographed in human history, but therein lay the challenge. The investigators analyzed 7,000 photos (sifted from 10,000) and 75 hours of video clips (from a raw total of 300 hours). How to piece together all these images? How to verify a precise time sequence for the collapses? How to predict the fire behavior and the course of damage in retrospect?

Thousands of images had no time stamps. Some were mistimed because of camera settings, and some were delayed because of broadcast delays on live television. Like making a painstaking pointillistic portrait, the investigators meticulously constructed a window-by-window profile for the four faces of each of the twin towers. From airplane strike to building collapse, fragments of information were knitted together by the models. A consistent and cohesive timeline emerged. Though the modeling process led to more questions, it also yielded the capacity to answer them. The results fed into the other modules of the overall investigation, contributing to a global simulation that unraveled the mystery of why the towers collapsed as they did. And over the longer term, the scrupulous analyses of the 9/11 failure modes led to design improvements with skyscrapers and structural steel.

If medical care that focuses only on intents and not on effects can have substantial social costs, then so can infectious disease models.

Similarly, it might never be possible to exactly predict earthquakes, but a conscious and direct engagement with reality can improve ways to engineer buildings that are more resistant to earthquakes. To design against such diverse events as terrorist attacks, earthquakes, and epidemics, accountable models are essential components of disaster preparedness. The conditions, contingencies, and caveats of these models will change, but the explanation accountability should be held constant.

Third is *enterprise accountability*. This stems from the old idea that if a pet bites someone or if a restaurant serves food that sickens people, the owners are responsible. In such cases the social good derives from personal responsibility, the philosopher Helen Nissenbaum notes. Using that logic, looking at the software industry

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[2] Medication Errors and Adverse Drug Events, Patient Safety Network, Agency for Healthcare Research and Quality, September 2019, https://tinyurl.com/y8epeoet; Goodman J, Villarreal P, Jones B. 2011. The social cost of adverse medical events, and what we can do about it. Health Affairs 30(4):590–95.

[3] Pitts W, Butler K, Junker V. 2005. Federal Building and Fire Safety Investigation of the World Trade Center Disaster: Visual Evidence, Damage Estimates, and Timeline Analysis (NIST NCSTAR 1-5A). Gaithersburg MD: National Institute of Standards and Technology.

where model development is prevalent, there is a vast "vacuum in accountability" compared with settings where owners are held responsible, Nissenbaum wrote in 1996.[4] It gets worse, because there's a "denial of accountability" seen in "written license agreements that accompany almost all mass-produced consumer software which usually includes one section detailing the producers' rights, and another negating accountability." Even in my own experience, one of the software tools I codeveloped came with a standard all-caps disclaimer absolving the corporation of any legal responsibility for damages its use might cause. And regularly, these sections are simply not read by users.

> *Expertise, no matter how rigorous and rational, can lead to false confidence when accountability is lacking.*

There are big differences between this approach and what's practiced in the construction industry. Using a case narrative from David McCullough's 1972 classic *The Great Bridge*, Nissenbaum has discussed how engineering firms use extra precautions for safety. When the caissons for the Brooklyn Bridge were being built in the 1870s, a mysterious malady affected the workers. For the suspension to work properly, the caissons had to be sunk to the deepest bedrock, about 80 feet below the ground, and be filled with brick and concrete to provide a firm foundation for the neo-Gothic towers. Returning from the caissons, workers would report severe pain, mostly in the knees, that proved to be a medical mystery. The pain endured for hours, even days, and triggered complications such as convulsions, vomiting, dizziness, and double vision.

Washington Augustus Roebling, the bridge's chief engineer, stayed longer in the caissons to boost morale among workers, only to suffer problems himself. Over four months he trained his wife, Emily Warren Roebling, on the bridge's details. (She became an exceptional engineer, and for the next 11 years directed construction of the bridge, which opened in 1883, while her husband was confined to a sick room, still retaining the "chief engineer" title.) Elevators were installed to replace spiral staircases to bring workers from the depths, but that exacerbated the calamity. It was later uncovered that the "caisson disease" was decompression sickness—the "bends"—resulting from significant pressure alterations due to altitude shifts. As the industrial practice improved, so did the enterprise accountability, hand in hand. Today, it is impossible to even imagine a modern bridge project without a decompression chamber supplied by the builders.

Holding Models Accountable

Failures in engineering systems are judged unforgivingly, and rightly so. Yet similarly consequential planning models are rarely held accountable. One can build a device as a do-it-yourself hobby project, but during a health crisis if that device is claimed to be a "ventilator" for clinical use, then a very different set of expectations, responsibilities, and rules applies. The same sensibility should apply to models: we need to separate the drive-through concessions of research exploration from the practical consequences of public health.

An old saw holds that the best parachute packers are those who jump. Expertise, no matter how rigorous and rational, can lead to false confidence when accountability is lacking. Modelers—myself included—feel comfortable talking about how models are incomplete and uncertain abstractions of the real world. But just as with exit row seating, that comfort should come at the price of a key responsibility: being accountable for not just applying rigor but transparently communicating to the public the assumptions and limitations that undergird even the best of models and intentions.

Practical accountability drives practical standards, as can be seen with improved and reliable construction models. Each of the three forms of accountability—effects, explanation, and enterprise—can strengthen models and approaches for modeling. This is critical, as lives and livelihoods depend on them.

During covid-19, as more people prefer contactless delivery and payments, we must remember that we pay a hefty price if the models are contactless with reality. These are times when bats can turn our world upside down, models are clashing with slogans, and lives in the multiples of 9/11 have been lost. Even small accountabilities will help—and may well foster better appreciation of, and support for, models that inform public policy in uncertain times.

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[4] Nissenbaum H. 1996. Accountability in a computerized society. Science and Engineering Ethics 2:25–42.

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