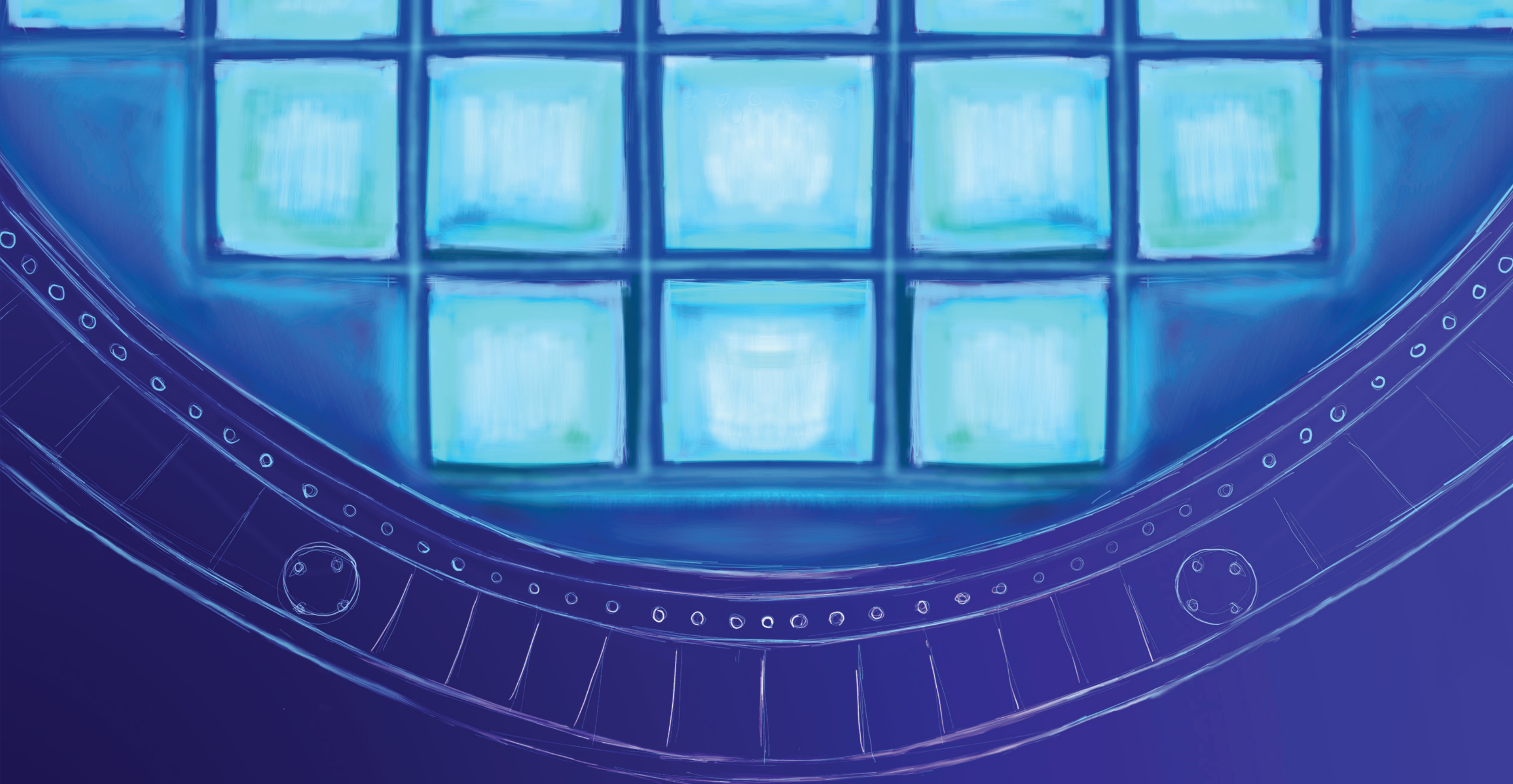

The Future of Nuclear Energy in a Carbon-Constrained World

AN INTERDISCIPLINARY MIT STUDY

Executive Summary

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Foreword and Acknowledgments

The MIT *Future of Nuclear Energy in a Carbon-Constrained World* study is the eighth in the MIT Energy Initiative's "*Future of*" series, which aims to shed light on a range of complex and important issues involving energy and the environment. A central theme is understanding the role of technologies that might contribute at scale in meeting rapidly growing global energy demand in a carbon-constrained world. Nuclear power could certainly play an important role, and it was the subject of the first of these interdisciplinary studies at MIT—the 2003 *Future of Nuclear Power* report. More recent studies have looked at the roles of CO_2 sequestration, natural gas, the electric grid, and solar power. Following a 2009 update to the original nuclear study, now is an appropriate time to take a fresh look at nuclear, given advances in inherently safer technologies, a sharpened focus on the need to reduce CO_2 emissions in the energy sector, and challenges of cost and public perceptions of safety.

The study is designed to serve as a balanced, fact-based, and analysis-driven guide for stakeholders involved in nuclear energy. Policy makers, utilities, existing and startup energy companies, regulators, investors, and other power-sector stakeholders can use this study to better understand the challenges and opportunities currently facing nuclear energy in the U.S. and around the world. The report distills results and findings from more than two years of primary research, a review of the state of the art, and quantitative modeling and analysis.

The MIT *Future of Nuclear Energy in a Carbon-Constrained World* study was supported by a number of sponsors and was complemented by a distinguished Advisory Committee and Review Team. We gratefully acknowledge the support of our major sponsor The Alfred P. Sloan Foundation and important contributions from Shell, Électricité de France (EDF), The David and Lucile Packard Foundation, General Atomics, the Anthropocene Institute, MIT's International Policy Laboratory, Mr. Zach Pate, Mr. Neil Rasmussen, and Dr. James Del Favero. We also thank the Idaho National Laboratory, Dominion Engineering Inc., Blumont Engineering Solutions (Paul Meier and his JuiceBox work for Chapter 1), Professor Giorgio Locatelli from the University of Leeds (for his work on Megaprojects in Chapter 2), the Breakthrough Institute, and Lucid Strategy for their generous in-kind contributions. We also wish to acknowledge Professor Jessika Trancik and Dr. James McNerny from the Institute for Data, Systems, and Society at MIT for their valuable input to the analysis of the cost breakdown of nuclear power plants.

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This report represents the opinions and views of the researchers, who are solely responsible for its content, including any errors. The Advisory Committee and the Reviewers are not responsible for the findings and recommendations it contains, and their individual opinions and views may differ from those expressed herein.

Dedicated to the memory of our friend and colleague Mujid Kazimi.

Executive Summary

Harnessing the power of the atomic nucleus for peaceful purposes was one of the most astonishing scientific and technological achievements of the 20th century. It has benefitted medicine, security, and energy. Yet, after a few decades of rapid growth, investment in nuclear energy has stalled in many developed countries and nuclear energy now constitutes a meager 5% of global primary energy production.

In the 21st century the world faces the new challenge of drastically reducing emissions of greenhouse gases while simultaneously expanding energy access and economic opportunity to billions of people. We examined this challenge in the electricity sector, which has been widely identified as an early candidate for deep decarbonization. In most regions, serving projected load in 2050 while simultaneously reducing emissions will require a mix of electrical generation assets that is different from the current system. While a variety of low- or zero-carbon technologies can be employed in various combinations, our analysis shows the potential contribution nuclear can make as a dispatchable low-carbon technology. Without that contribution, the cost of achieving deep decarbonization targets increases significantly (see Figure E.1, left column). The least-cost portfolios include an important share for nuclear, the magnitude of which significantly grows as the cost of nuclear drops (Figure E.1, right column).

Despite this promise, the prospects for the expansion of nuclear energy remain decidedly dim in many parts of the world. The fundamental problem is cost. Other generation technologies have become cheaper in recent decades, while new nuclear plants have only become costlier. This disturbing trend undermines nuclear energy's potential contribution and increases the cost of achieving deep decarbonization. In this study, we examine what is needed to arrest and reverse that trend.

We have surveyed recent light water reactor (LWR) construction projects around the world and examined recent advances in cross-cutting technologies that can be applied to nuclear plant construction for a wide range of advanced nuclear plant concepts and designs under development. To address cost concerns, we recommend:

(1) *An increased focus on using proven project/construction management practices to increase the probability of success in the execution and delivery of new nuclear power plants.*

The recent experience of nuclear construction projects in the United States and Europe has demonstrated repeated failures of construction management practices in terms of their ability to deliver products on time and within budget. Several corrective actions are urgently needed: (a) completing greater portions of the detailed design prior to construction; (b) using a proven supply chain and skilled workforce; (c) incorporating manufacturers and builders into design teams in the early stages of the design process to assure that plant systems, structures, and components are designed for efficient construction and manufacturing to relevant standards; (d) appointing a single primary contract manager with proven expertise in managing multiple independent subcontractors; (e) establishing a contracting structure that ensures all contractors have a vested interest in the success of the project; and (f) enabling a flexible regulatory environment that can accommodate small, unanticipated changes in design and construction in a timely fashion.

(2) *A shift away from primarily field construction of cumbersome, highly site-dependent plants to more serial manufacturing of standardized plants.*

Opportunities exist to significantly reduce the capital cost and shorten the construction schedule for new nuclear power plants. First, the deployment of multiple, standardized units, especially at a single site, affords considerable learning from the construction of each unit. In the United States and Europe, where productivity at construction sites has been low, we also recommend expanded use of factory production to take advantage of the manufacturing sector's higher productivity when it comes to turning out complex systems, structures, and components. The use of an array of cross-cutting technologies, including modular construction in factories and shipyards, advanced concrete solutions (e.g., steel-plate composites, high-strength reinforcement steel, ultra-high performance concrete), seismic isolation technology, and advanced plant layouts (e.g., embedment, offshore siting), could have positive impacts on the cost and schedule of new nuclear power plant construction. For less complex systems, structures, and components, or at sites where construction productivity is high (as in Asia), conventional approaches may be the lowest-cost option.

It is important to emphasize the broad applicability of these recommendations across all reactor concepts and designs. Cost-cutting opportunities are pertinent to evolutionary Generation-III LWRs, small modular reactors (SMRs), and Generation-IV reactors.[1] Without design standardization and innovations in construction approaches, we do not believe the inherent technological features of any of the advanced reactors will produce the level of cost reductions needed to make nuclear electricity competitive with other generation options.

In addition to its high cost, the growth of nuclear energy has been hindered by public concerns about the consequences of severe accidents (such as occurred at Fukushima, Japan in 2011) in traditional Generation-II nuclear power plant designs. These concerns have led some countries to renounce nuclear power entirely. To address safety concerns, we recommend:

(3) *A shift toward reactor designs that incorporate inherent and passive safety features.*

Core materials that have high chemical and physical stability, high heat capacity, negative reactivity feedbacks, and high retention of fission products, together with engineered safety systems that require limited or no emergency AC power and minimal external intervention, will likely make operations simpler and more tolerable to human errors. Such design evolution has already occurred in some Generation-III LWRs and is exhibited in new plants built in China, Russia, and the United States. Passive safety designs can reduce the probability that a severe accident occurs, while also mitigating the offsite consequences in the event an accident does occur. Such designs can also ease the licensing of new plants and accelerate their deployment in developed and developing countries. We judge that advanced reactors like LWR-based SMRs (e.g., NuScale) and mature Generation-IV reactor concepts (e.g., high-temperature gas reactors and sodium-cooled fast reactors) also possess such features and are now ready for commercial deployment. Further, our assessment of the U.S. and international regulatory environments suggests that the current regulatory system is flexible enough to accommodate licensing of these advanced reactor designs. Certain modifications to the current regulatory framework could improve the efficiency and efficacy of licensing reviews.

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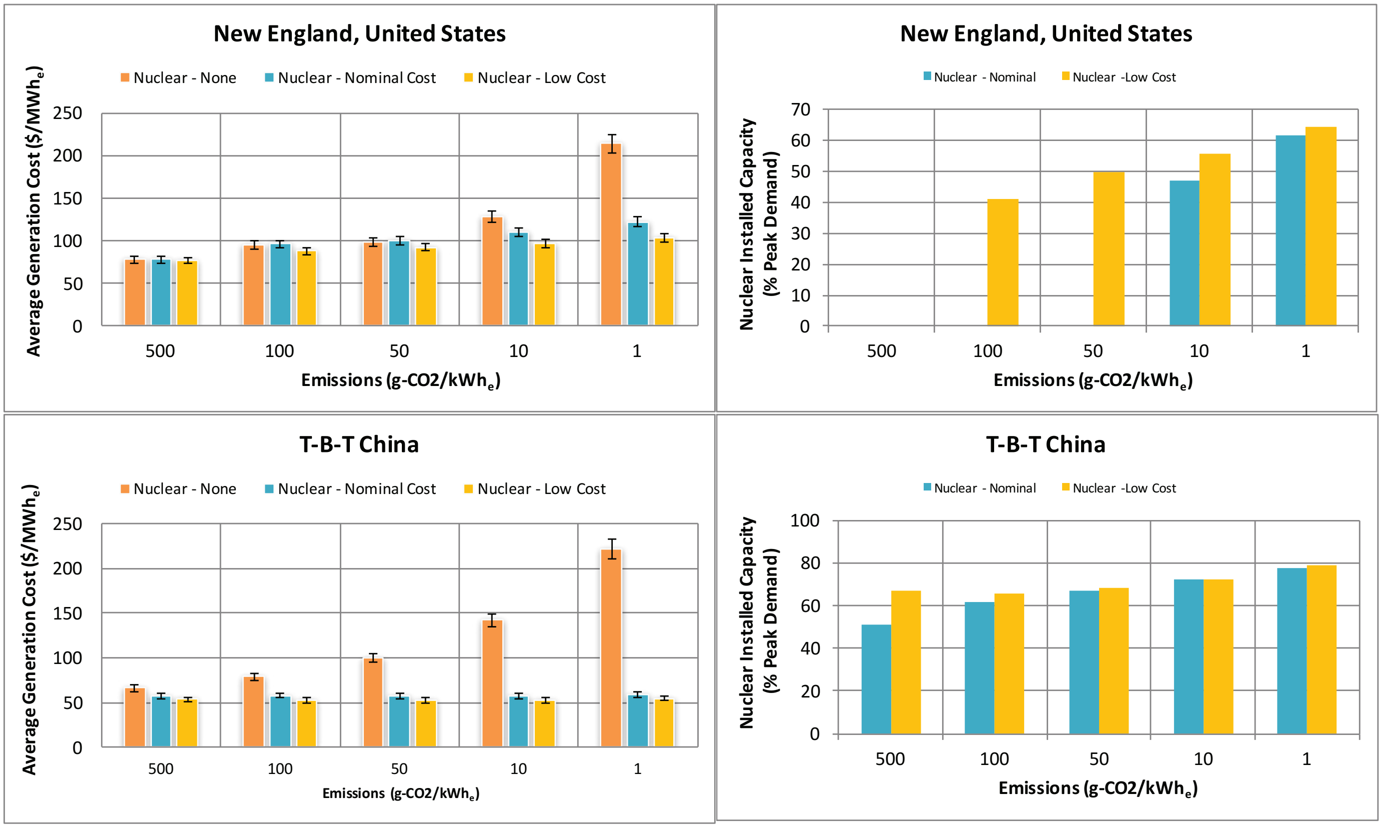
[1] Reactor designs are frequently classified into four generations. The first commercial nuclear reactors built in the late 1950s and 1960s are classified as Generation-I systems. Generation-II systems include commercial reactors that were built from 1970 to 1990. Generation-III reactors are commercial designs that incorporate evolutionary improvements over Generation-II systems. Generation-IV is the classification used to describe a set of advanced reactor designs that use non-water coolants and are under development today.

Figure E.1: (left) Average system cost of electricity (in $\$/\text{MWh}_e$) and (right) nuclear installed capacity (% of peak demand) in the New England region of the United States and the Tianjin-Beijing-Tangshan (T-B-T) region of China for different carbon constraints ($\text{gCO}_2/\text{kWh}_e$) and three scenarios of various available technologies in 2050: (a) no nuclear allowed, (b) nuclear is allowed at nominal overnight capital cost ($5,500 per kW_e for New England and $2,800 per kW_e for T-B-T), and (c) nuclear is allowed with improved overnight capital cost ($4,100 per kW_e for New England and $2,100 per kW_e for T-B-T)



Simulations were performed with an MIT system optimization tool called GenX. For a given power market the required inputs include hourly electricity demand, hourly weather patterns, economic costs (capital, operations, and fuel) for all power plants (nuclear, wind and solar with battery storage, fossil with and without carbon capture and storage), and their ramp-up rates. The GenX simulations were used to identify the electrical system generation mix that minimizes average system electricity costs in each of these markets. The cost escalation seen in the no-nuclear scenarios with aggressive carbon constraints is mostly due to the additional build-out and cost of energy storage, which becomes necessary in scenarios that rely exclusively on variable renewable energy technologies. The current world-average carbon intensity of the power sector is about 500 grams of CO_2 equivalent per kilowatt hour (g/kWh_e); according to climate change stabilization scenarios developed by the International Energy Agency in 2017, the power-sector carbon intensity targets to limit global average warming to 2°C range from 10 to 25 g/kWh_e by 2050 and less than 2 g/kWh_e by 2060.

Lastly, key actions by policy makers are also needed to capture the benefits of nuclear energy:

(4) *Decarbonization policies should create a level playing field that allows all low-carbon generation technologies to compete on their merits.*

Investors in nuclear innovation must see the possibility of earning a profit based on selling their products at full value, which should include factors such as the value of reducing CO_2 emissions that are external to the market. Policies that foreclose a role for nuclear energy discourage investment in nuclear technology. This may raise the cost of decarbonization and slow progress toward climate change mitigation goals. Incorporating CO_2 emissions costs into the price of electricity can more equitably recognize the value to all climate-friendly energy technologies. Nuclear generators, both existing plants and the new builds, would be among the beneficiaries of a level, competitive playing field.

(5) *Governments should establish reactor sites where companies can deploy prototype reactors for testing and operation oriented to regulatory licensing*.

Such sites should be open to diverse reactor concepts chosen by the companies that are interested in testing prototypes. The government should provide appropriate supervision and support—including safety protocols, infrastructure, environmental approvals, and fuel-cycle services—and should also be directly involved with all testing.

(6) *Governments should establish funding programs around prototype testing and commercial deployment of advanced reactor designs using four levers: (a) funding to share regulatory licensing costs, (b) funding to share research and development costs, (c) funding for the achievement of specific technical milestones, and (d) funding for production credits to reward successful demonstration of new designs.*

Many more findings emerged in the course of the research undertaken for this study. A detailed discussion of these findings is contained in the overview and main body of the study report, which is organized into five major topic areas (with corresponding chapter titles): Opportunities for Nuclear Energy, Nuclear Power Plant Costs, Advanced Reactor Technology Evaluation, Nuclear Industry Business Models and Policies, and Nuclear Reactor Safety Regulation and Licensing.

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