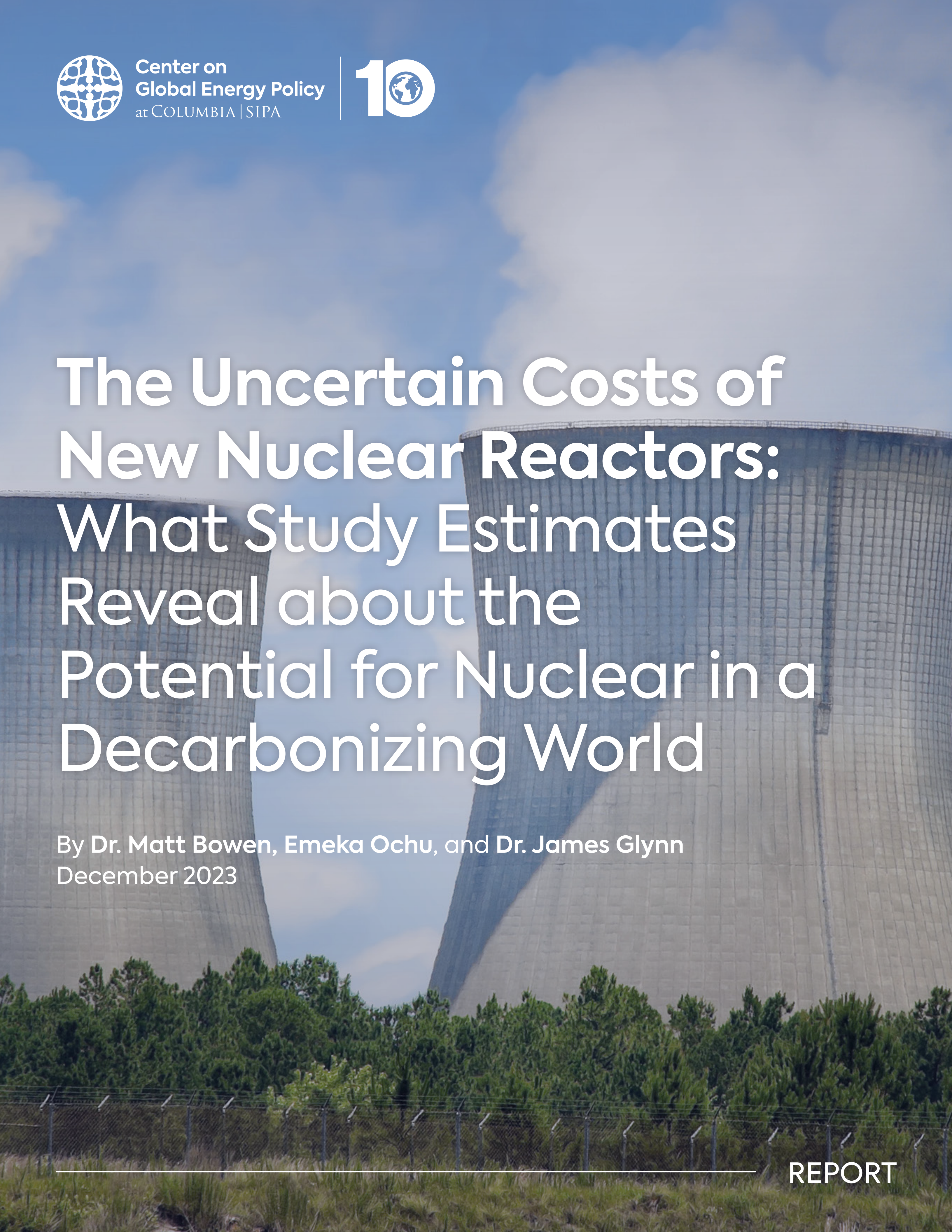

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The Uncertain Costs of New Nuclear Reactors: What Study Estimates Reveal about the Potential for Nuclear in a Decarbonizing World

By **Dr. Matt Bowen**, **Emeka Ochu**, and **Dr. James Glynn**

December 2023

REPORT

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Table of Contents

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He is an EU-commission invited expert in energy systems modeling and a reviewer of the EU Commission's DG-ENER new energy systems model METIS. He has given expert witness testimony to government committees on carbon capture and storage (CCS), carbon budgets, and net-zero carbon energy systems transition. He has served on the scientific advisory boards for multiple national and European research projects, such as the German DLR BEAM-ME project on high-performance optimization algorithms. He collaborates on numerous international energy-climate networks, including the Integrated Assessment Modelling Consortium (IAMC) and JPI-Climate. He is an affiliate invited member of the IEA-ETSAP executive committee. He has successfully led multiple national and international research & consulting project consortia.

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He holds two masters degrees (NUIG, Strathclyde) and a PhD (UCC) in areas related to energy systems analysis across engineering, science, and economics. He has affiliations with the Science Foundation Ireland MaREI Centre in University College Cork (UCC) and the engineering faculty in Imperial College London.

Executive Summary

Models that run decarbonization scenarios to meet mid-century goals for mitigating climate change almost always include a significant role for nuclear energy. The source's projected level of deployment, however, remains uncertain, largely due to a wide range of estimated costs for new builds. Other factors that make it hard to gauge nuclear's portion of the future energy mix include whether policies advancing low-carbon technologies will be enacted, the degree of public support for transmission siting and available low-carbon energy sources, whether new reactor technologies and fuels will change the investment equation, and how quickly "competitor" sources such as carbon capture and sequestration, renewables, and storage reduce costs.

This report, part of ongoing research into nuclear energy at the Center on Global Energy Policy at Columbia University SIPA, examines the economics of new nuclear facilities for electricity generation—whether building them out makes sense financially as part of efforts to reduce greenhouse gas emissions as power demand grows across the globe. Insights into costs can be gleaned by reviewing the history of construction delays and cost overruns in the United States, international experiences that have fared better and worse, and studies that model a transitioning energy system. Studies reviewed in this report estimate new US reactor costs generally ranging from $3,000/kilowatt (kW) to $6,200/kW based on a variety of reactor designs and cost reduction curves assumed for subsequent years. Internationally, new reactor costs vary significantly by country, depending in part upon factors such as the cost of labor and whether projects involve multiple reactor builds (with attendant efficiencies in manufacturing and construction).

Additional findings from this report include the following:

- The limited number of new reactor builds in the United States in recent decades and the large number of new designs under development (some of which have never been built anywhere in the world) leave few data points from which to draw definitive conclusions on future nuclear costs.
- In countries such as China and India, construction expertise and supply chain efficiencies from ongoing nuclear power project buildouts and energy technology learning as well as lower labor costs, among other factors, have created more competitive economics for nuclear than are currently found in the United States.
- Modeling of nuclear energy costs in the US suggests that if the price tag ends up being much higher than the upper limits used in the studies cited, such as above $6,200/kW, new nuclear

will play a marginal role, if any, in the US energy transition.

- Within the cost range quoted above, nuclear's ability to play a substantial role in the United States (e.g., 50 gigawatts of deployment) could depend on factors including whether stronger decarbonization policies are enacted; whether other viable firm, low-carbon options emerge as competitive alternatives; whether difficulties with siting new transmission lines continue; and/or whether renewable energy expansion faces constraints.
- The new 30 percent tax credit in the Inflation Reduction Act available to both renewable and nuclear energy will substantially lower the cost of new nuclear reactors for US utilities.
- Internationally, scenarios by the Intergovernmental Panel on Climate Change project that lower reactor costs in some emerging countries, in combination with strict climate mitigation policies, could result in very large new nuclear capacity expansion there.
- In modeling cases with high *variable* low-carbon power sources, the need for firm sources and storage options may be underestimated in the absence of greater temporal and technical granularity. This practice may omit costs associated with flexibility, market reserve, and storage that could be ameliorated by dispatchable nuclear capacity.

I. Introduction

Nuclear energy plays a material role in the energy mix of most models running net-zero carbon scenarios.[1] Models of every kind benefit from robust inputs, but many factors surrounding nuclear energy's future are uncertain, from whether stronger policies advancing low-carbon technologies will be enacted, to any shifts in public support for nuclear, renewables, and transmission siting, to advancements in reactor technologies and fuels, to strides in "competitor" sources such as renewables and storage. But in most countries, one important factor remains elusive: direct costs of building a new nuclear reactor.

Nuclear build experiences vary greatly. Some face longer delays and higher cost overruns due to factors such as contractor mismanagement or a need to adjust specifications midstream to meet changing regulatory requirements. New reactor builds in the United States have been very limited in number in recent decades, and there are a large number of new designs under development (some of which involve reactor types that have never been built anywhere in the world), thus there are not yet data points from which to draw definitive conclusions about nuclear costs. Experiences in different countries also vary greatly for all of these reasons and more, including for projects involving multiple builds that further the learning curve and, with it, efficiency in manufacturing and construction.

Given the many factors affecting a nuclear reactor's ultimate price tag, it's worth considering possible ranges of future costs that may be incorporated into models for planning the energy transition to meet global climate goals, as they impact nuclear energy's ability to address energy and environmental challenges. Toward this end, this report first relates some historical experience of reactor construction, both in the United States and selected examples internationally, to illustrate the mixed record of reactor construction management. It then analyzes the shifting policy landscape and other dimensions that may alter the economics and deployment of new nuclear going forward in the United States and notes that similar dynamics may exist in other countries. Next, it compiles reactor cost estimate ranges from nine studies on nuclear's future in the United States and internationally. Finally, it examines a best-in-class modeling exercise focused on what reaching different temperature thresholds through efforts at limiting greenhouse gas emissions might translate to in reactor costs over time outside the US. The estimated cost ranges from the studies and modeling exercise illustrate the impact of uncertainty of cost variation on the role of nuclear power in decarbonization scenarios internationally. The report concludes with consideration of the interplay of factors that affect reactor economics and their implications for the future of nuclear energy in decarbonization efforts toward achieving the Paris Agreement goals.

II. A Selected History of Cost Overruns for US Reactor Construction, including the AP1000

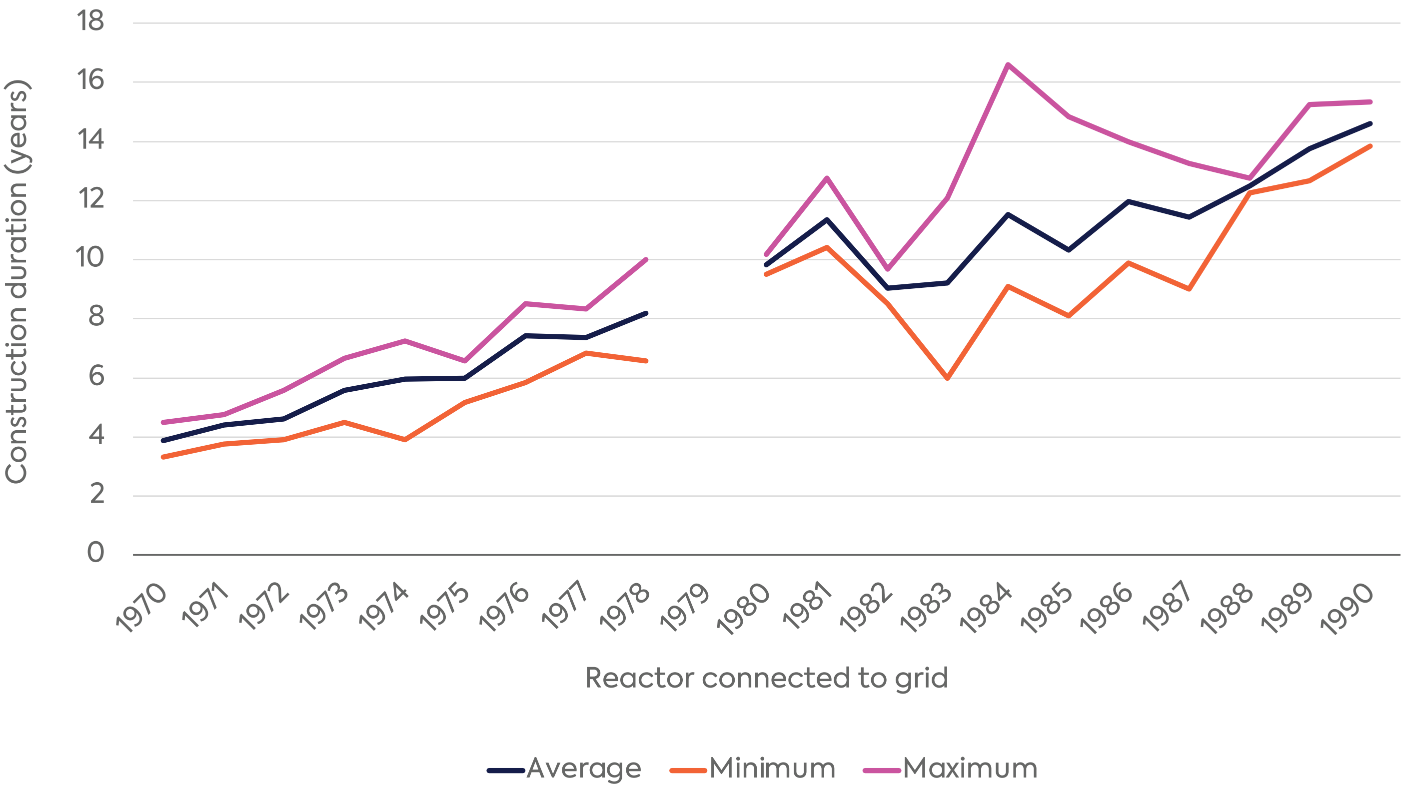
There is little agreement in academic literature about how much new nuclear reactors would help in the transition to a zero-carbon electrical grid[2] in light of high-profile cost overruns at recent projects in the West and falling costs for renewable energy sources.

Reactor construction in the United States has a checkered history that includes projects built in fewer than four years as well as ones that experienced protracted construction delays of greater than 10 years along with massive cost overruns. For example, over just a 10-year period (1968–78), overnight costs (or the costs of a construction project excluding any interest) for US reactor projects varied tremendously, from around $2,000 per kilowatt (kW) to over $12,000/kW (2017$).[3] The variation in construction schedules, affecting cost, fluctuated wildly in even short time periods: among the 45 US power reactors that began construction between 1966 and 1968, the time to enter into commercial operation ranged from under four years to nearly 17 years.[4]

US reactor construction projects in the early decades of nuclear energy development regularly went significantly over initial budgeted cost estimates. Of the 75 nuclear plants built between 1966 and 1977, cost overruns averaged 207 percent. Following the Three Mile Island accident in 1979, cost overruns grew, averaging 250 percent for the next 40 plants constructed.[5] Congressional testimonies at the time apportioned blame for the schedule delays, cost overruns, and cancellations to a variety of sources: construction mismanagement by private entities, design changes required by revised US Nuclear Regulatory Commission (NRC) regulations, interventions by antinuclear groups, lower electricity demand growth than forecasted, and high inflation rates.[6]

Contemporary studies[7] delved into the drivers behind the schedule delays and cost overruns in the 1970s and 1980s, and more recent analysis has assessed that declining labor productivity and certain "soft" costs, such as labor supervision, were leading contributors to cost escalation in this earlier round of builds.[8] Figure 1 shows a rising average range of construction duration over these two decades. When inflation rates rose in the late 1970s and early 1980s to over 10 percent at times, construction delays became even more damaging to nuclear power plant economics.

Figure 1: Construction duration for US reactors connected between 1970 and 1990



Note: "Construction duration" is defined as from start of construction to grid connection. There were no US reactors connected to the grid in 1979, so there are no data points for that year. From grid connection to commercial operations may take anywhere from a couple of months to much longer.

Source: International Atomic Energy Agency Power Reactor Information System database.

There are limited data points in recent decades for what it costs to build a nuclear power plant in the United States. Prior to 2023, the last two reactors connected to the US electrical grid were Watts Bar 1 and 2 in Tennessee, which were connected in 1996 and 2016, respectively. Both units had begun construction in 1973, but their construction was halted in 1985 after the NRC identified weaknesses in Tennessee Valley Authority (TVA)'s nuclear program.[9] TVA resumed construction of Watts Bar 1 in 1992 and that reactor began commercial operations in 1996. TVA resumed construction of Watts Bar 2 in 2007 and achieved commercial operations in 2016. Even the resumed construction of Watts Bar 2 experienced delays and cost overruns, however: it was thought the construction could be finished in five years and at a cost of $2.5 billion, but the actual cost ended up being $4.7 billion.[10]

The experience of the first truly "new" nuclear reactors to begin construction in the United States was, similar to the overall experience in the 1970s and 1980s, subject to delays and cost overruns. When construction on two Westinghouse AP1000 reactors in Georgia was approved in 2009, the two 1,117 megawatt electric (MWe) reactors were estimated to cost $14 billion and begin commercial operations in 2016 and 2017.[11] But in 2017 the reactors were not even close to finished, and the magnitude of their construction problems finally became apparent to the public. Westinghouse declared bankruptcy due to losses sustained in the projects, and utilities that were building two AP1000s in South Carolina decided not to finish them after $9 billion in expenditures.[12] Recent reports estimate the costs for the two AP1000s at the Vogtle site in Georgia, the first of which began commercial operations in July 2023, will top $30 billion,[13] more than double both the original estimated cost and time of construction.

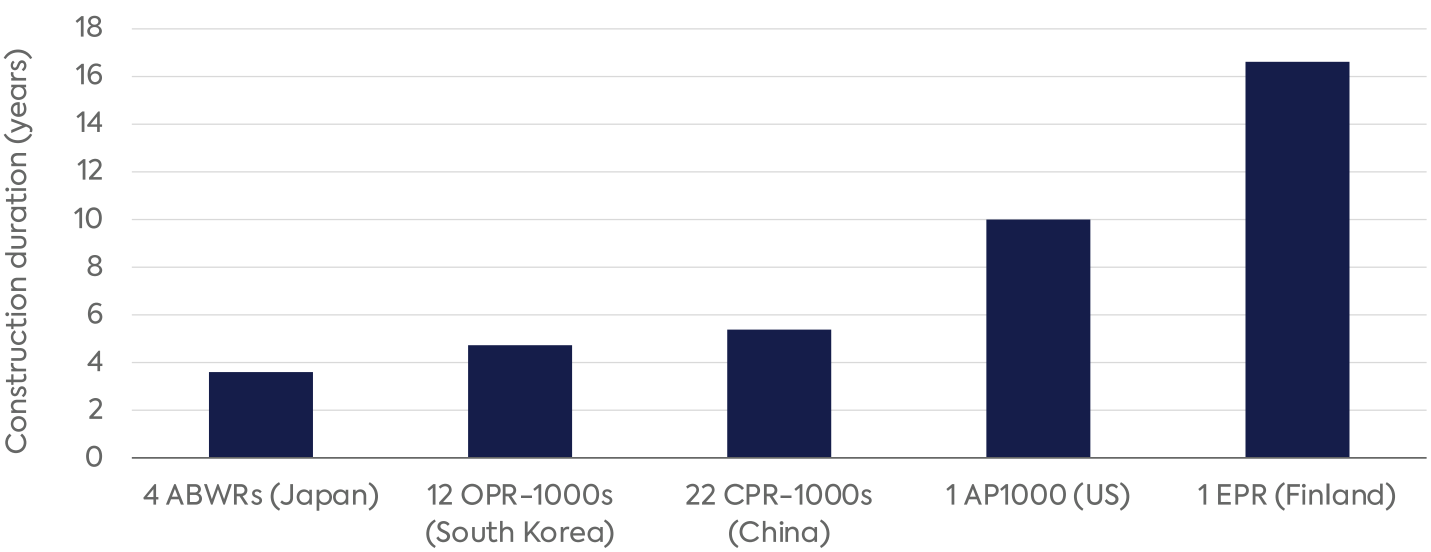
Regardless of the exact root causes of the AP1000 projects' schedule and cost overruns— discussed at length in many studies[14]—their example has only reinforced the reputation for negative construction experiences in the United States. The international experience is rather more mixed, and may point to avenues for improvement.

III. A Mixed Experience of Reactor Builds outside the United States

Among other high-profile first-of-a-kind (FOAK) Western reactors under construction, the French EPR has experienced an even more inauspicious outcome than the AP1000. The first EPR began construction at the Olkiluoto site in Finland in 2005 and only began commercial operations in April 2023, and its estimated cost is about three times its initial cost estimate.[15] The EPR under construction in France is more than 10 years behind schedule and the projected cost has grown to more than four times its initial estimate, to 13.2 billion euros.[16]

However, in terms of the global nuclear energy picture, the two AP1000 builds in the United States and the EPR build in Finland are only three data points among 68 reactors connected to national grids during the previous decade (2012 to 2022). In addition, as Figure 2 shows, over the past several decades other reactor designs have been built in series and in much shorter periods than the AP1000 or EPR, and in both Organisation for Economic Co-Operation and Development (OECD) nations, as well as non-OECD countries.[17] These include FOAK reactors such as the ABWR in Japan, where each of the first two units were built in four years.

Figure 2: Average construction duration for three selected reactor series, one AP1000, and one EPR



Note: "Construction duration" is defined as from start of construction to grid connection. Using this metric, the two EPRs built in China (not shown in this chart) took on average 8.9 years, and the four AP1000s built in China (also not shown in this chart) took on average 8.8 years. Vogtle 3 is the one AP1000 in the US represented.

Source: International Atomic Energy Agency, Power Reactor Information System.

While construction duration is a useful (and transparent) indicator of the discipline of the team building a given reactor, it is not the same as cost, and it can be difficult to know what the costs of a given project were. As a Massachusetts Institute of Technology study from 2018 noted,[18] while four APR1400 reactors built by South Korean companies in the United Arab Emirates between 2012 and 2023 (Unit 4 is nearing commercial operations) were reportedly contracted for roughly $3,500 per kilowatt (kW) in overnight costs, it isn't clear what expenses are included in this number, nor whether this is what it cost the South Korean consortium to build these power plants.

These points notwithstanding, there are indicators[19] that what Figure 2 suggests is likely valid: some countries, such as China, have achieved lower reactor costs by managing reactor construction in less time, as well as other factors (such as lower labor rates). An International Energy Agency (IEA) study[20] in 2021 on reaching net zero emissions estimated large variances in overnight costs for nuclear reactor builds depending on the country or region of their siting. Estimates for 2020 were $2,800/kW for China and India, but $5,000/kW for the US and $6,600/kW for the European Union.

The S&P Global World Energy Power Plant (WEPPS) database[21] includes the year for which all nuclear power plants became operational, or the expected year of completion for plants under construction, as well as expectations for delayed projects and projects planned or still in the design or pre-development stages. Analysis from WEPPS data gives us some insight into the construction lead time of nuclear power projects globally. While some countries, such as China, have proved capable of building nuclear plants faster, in as little as four years, construction in other geographies is expected to take up to eight years from commencement, while planning for some nuclear plants is taking up to 20 years. This is considerably longer than the four-year lead time typically assumed in energy systems optimization models or integrated assessment models, if the parameter is included at all,[22] suggesting that the feasible deployment rate of new nuclear capacity within decarbonization scenarios is uncertain and potentially lower than currently indicated.

Construction time (as a proxy for labor costs) remains a key variable affecting the economics of nuclear power plants globally, though other technical and non-technical factors will also influence the future role nuclear power might play in reaching net-zero emissions goals.

IV. Additional Factors Affecting the Deployment of New Nuclear Reactors

The AP1000 costs in Georgia are roughly 15–25 times the unit overnight capital cost of alternate zero-carbon power sources. Renewable energy sources have rapidly been declining in cost per unit installed capacity, to the point where in many countries wind and solar now commonly have lower levelized costs of electricity generation (LCOE)[23] than nuclear-generated electricity, and can be built quicker and easier. Even if construction of the first AP1000s or EPR had met cost and lead-time estimates, it's not clear that the reactors would have been economically competitive in terms of LCOE with other power generation sources such as renewables, or even with fossil-fuel-dependent but more efficient new natural gas combined cycle (NGCC) plants, for example.[24]

On the other hand, while the calculated LCOE for new wind and solar projects in the United States may be lower than that of nuclear plants or other "firm/dispatchable" (that is, available when needed) plants, this is not a complete accounting of the value proposition for a utility deploying either source.[25] Variable resources such as wind do not contribute in the same way as dispatchable resources to meeting rising peak demand for electricity and meeting reliability metrics. Since any utility approach to decarbonization will also have to maintain affordability and reliability, some have proposed new advanced nuclear facilities as part of decarbonization strategies, even with the expected greater LCOE as compared to wind and solar.[26] A utility could decide to purchase energy storage facilities to help "firm" up the variable renewable energy generation, though this would inevitably involve additional costs; a recent Lazard report assessed that adding storage to renewable energy systems substantially raised the LCOE of combined energy and storage systems in some regions of the United States.[27]

Several possible future developments, including those discussed below, could alter the economics and deployment of new nuclear reactors. Climate policies to reduce greenhouse gas (GHG) emissions alter the competitiveness within power markets, aiding low-carbon power generation technologies with polluter-pays principles and policies endogenizing damages from carbon-intensive power plants. Technology innovation and improvements in public support may also reduce construction time and overnight capital costs.

Policies to Reduce Air Pollution and Greenhouse Gas Emissions

Policies focused on air pollution and climate change could considerably change the economic picture for new nuclear power plants. Under current US policies, however, recent models (focusing on analysis of the US nationally determined contribution, the US Inflation Reduction Act [IRA] of 2022, and Paris Agreement–consistent scenarios from the Intergovernmental Panel on Climate Change [IPCC]) demonstrate that new nuclear capacity in the US will be limited at present reactor costs. The US currently has no comprehensive economy-wide price for emitting carbon dioxide (CO_2), methane (CH4), or any other greenhouse gas, despite climate-change-related damages increasing.[28] A market mechanism requiring payment for GHG emissions (or restricting the emissions outright) would make nuclear more cost-competitive with fossil fuels for electricity generation.

The IRA provides a technology-neutral 30 percent tax credit that both renewable and nuclear projects can qualify for, which will help to substantially lower new nuclear reactors' costs to US utilities. Given that the IRA passed in August 2022, its effects are still being assessed, though they could be substantial. However, a recent analysis on the impact of the IRA on power sector decarbonization by Bistline et al.,[29] leveraging results from nine independent, state-of-the-art models, shows generation shares from low-emitting technologies—including renewables, nuclear, and carbon capture and storage (CCS)—in 2030 varying between 49 and 82 percent (68 percent average) across models with IRA, up from about 40 percent in 2023, and from 46 to 65 percent without IRA (54 percent average), an 11 to 33 percentage point increase. The range for power sector generation outcomes under the IRA becomes narrower by 2035, varying between 30 and 38 percent across models. Specifically, the analysis indicates that IRA provisions contribute to the continued operation of existing nuclear plants, recognizing their ongoing contribution to low-carbon electricity generation in varying magnitudes across the models, depending on availability of tax credits, market dynamics, and technological developments. Another analysis by the US Department of Energy's Loan Programs Office (LPO) estimated that the IRA's tax credit would change a potential nuclear FOAK LCOE of $102 per megawatt-hour (MWh) to $85/MWh and a potential "Nth-of-a-kind" (NOAK, or later generation) LCOE of $76/MWh to $66/MWh.[30]

In addition, several states have passed legally binding climate policies that require their power sectors to be completely decarbonized by roughly mid-century.[31] Any "clean energy standards" that allow nuclear power to compete improve the economic landscape for new reactors.

One specific example of how state clean energy standards alter the economic considerations surrounding new nuclear involves Washington state's passage of a clean energy law in 2019 requiring its power sector to be zero carbon by 2045.[32] Nuclear power was included as an eligible source of clean energy, and analyses conducted by the company E3 showed that new reactors would help reduce electricity costs to consumers by avoiding a massive overbuild of variable renewable generation and/or storage capacity necessary to assure reliable supply.[33] Similarly, the Net Zero America study by Princeton estimated that hundreds of gigawatts of new low-carbon, firm power would be required by 2050 to meet deep decarbonization scenarios.[34] Using overnight costs of $5,500/kW to $6,400/kW (2016$) for nuclear plants, the study estimated that new reactors could play a role in helping limit the costs associated with reducing GHG emissions while maintaining grid reliability.

New Approaches to Reactor Construction

Another development that could change the prospects for new nuclear is if developers can find ways to reduce costs and schedules. Private companies have made a variety of claims about low expected overnight costs, with some estimating that they may even be able to reach $2,100/kW at NOAK deployment.[35] However, cost estimates are highly uncertain for early-stage projects,[36] and recent history in the United States suggests that reactor cost estimates tend to be revised upwards over time as designs reach greater maturity.[37]

Studies have found a number of pathways that could be fruitful in reducing reactor construction costs.[38] Several factors are so widely assumed to be needed for successful construction outcomes that they are not discussed below: high design maturity at the start of construction, design standardization for subsequent builds, suppliers experienced in manufacturing nuclear-grade components, effective project management techniques, contracts that reward performance, and a stable and predictable regulatory environment. In addition, several other aspects related to reactor design and construction might lower costs:

Smaller Reactors

The theoretical gain in economies of scale for larger reactors has—at least in the US experience—been offset by construction schedule delays, where the added financing charges during longer construction periods has diminished the benefits of economies of scale. The US Department of Energy noted this in a 1986 report with respect to prior US reactor builds.[39]

There is also evidence from France's experience in building pressurized water reactors between the 1970s and the 2000s that suggests the scale-up in power levels (900 gigawatts [GW]; 1,300 GW; 1,450 GW) led to reactors that were more expensive on a per-megawatt (MW) basis,[40] even before the gargantuan 1,650 MW EPR reactor was developed. The French government published reactor cost data for its historical fleet in 2012, and subsequent analysis found evidence of a cost-reducing learning effect when the same reactor design was built repeatedly.[41]

Smaller reactors would, at a minimum, represent a smaller amount of capital expenditures for utilities, and thus a corresponding smaller amount of financial risk that would result from schedule overruns.

Modular Construction Techniques

The idea behind "modular construction" is to move at least some construction activities away from plant sites, where they are exposed to the elements, and into controlled factory environments. In the United States, labor rates are high compared with other countries, while labor productivity in the construction industry has declined, making modular construction techniques potentially attractive.[42] Industry has successfully applied modular construction techniques to non-nuclear projects for many decades, and some examples, such as Japan's ABWR,[43] prove its applicability to nuclear construction projects as well

There are some tradeoffs to using modular construction: while it might reduce efforts and costs at a nuclear power plant site, it implies additional costs at a factory site as well as potentially increased project risk if, for example, the modules are made incorrectly at the factory and shipped to the construction site before the problems are discovered. (This happened with modules made at the Lake Charles facility in Louisiana for the AP1000s in Georgia and South Carolina.[44])

Sequential Builds at the Same Site with the Same Workforce.

Building the same reactor design multiple times at the same site with the same workforce, and staggering the builds, raises the prospects of greater efficiency through learning and, with it, the possibility that later reactor builds will have shorter construction times and lower costs. The South Korean APR1400 project in the United Arab Emirates, for example, had a 40 percent reduction in labor costs between the construction of Units 1 and 4.[45]

Additional Sources of Potential Cost Reductions.

Other cost reductions are plausible, including through advanced fuels, advanced concrete, robotics, and more. MIT concluded that the introduction of such factors could reduce overnight costs for US reactors by 25–30 percent from its 2009 estimate of $5,000/kW.[46]

Public Support

Support for nuclear around the world, as expressed by both governments and financial institutions, is a mixed bag of appreciating the energy source's low emissions use while acknowledging a sometimes wary public.[47] Public support for nuclear in the US varies,[48] but a dozen states have laws restricting the construction of new nuclear power facilities (California, Connecticut, Hawaii, Illinois, Maine, Massachusetts, Minnesota, New Jersey, New York, Oregon, Rhode Island, and Vermont).[49] Some states have repealed their prohibitions in recent years (e.g., Montana in 2021 and West Virginia in 2022), and it is at least plausible that advanced reactors with greater inherent safety may help reduce capital and operating cost, and even lead to greater public acceptance of the power source.

Advancing spent nuclear fuel management (especially on US disposal capacity for long-lived nuclear waste) might also further nuclear's prospects for playing a meaningful role in the energy transition, especially in states that currently prohibit new reactors unless such progress is made.

But public opposition has arisen in connection with other non-nuclear elements of decarbonization strategies that could also affect nuclear's reach. For example, transmission lines in the US have been slow to permit and build.[50] (Even renewable energy projects have encountered local opposition that some studies have assessed to be "widespread and growing."[51])

In emerging economies such as China and India, support for new nuclear reactor projects is seen in the considerable drive to scale nuclear power generation. China currently has 21 nuclear reactors under construction with a generation capacity of about 21.61 GW of electricity.[52] India has the second-largest nuclear buildout, with eight reactors under construction that will be able to generate more than 6 GW of electricity. Two key factors fueling India's buildout are the need to meet increased electricity demand and a need to reduce reliance on coal, which is part of the country's decarbonization strategy.[53]

V. Examples of Estimated US and Select International Nuclear Reactor Costs

Numerous studies have been published in recent years containing overnight cost estimate ranges for new nuclear power plants and how they are expected to change with deployments over time. The results of nine high-profile policy studies on the role of nuclear in decarbonization scenarios—eight focused on the US and one on several countries and regions—are briefly reviewed below. Viewed together, the US estimates illustrate theoretical uncertainty over costs, and the international costs illustrate regional variances. The studies estimate future US reactor costs generally ranging from $3,000/kW to $6,200/kW, depending on the reactor design and a variety of cost reduction curves assumed for subsequent years. The IEA's international study includes reactor costs in other countries ranging from $2,500/kW to $6,600/kW. Details from each study follow.

The Massachusetts Institute of Technology (MIT) published a study[54] in 2018 that modeled a NOAK "low" new nuclear cost to be $4,100/kW, a NOAK "nominal" new nuclear to be $5,500/kW, and a NOAK "high" new nuclear to be $6,900/kW (2017$). (The low and high estimates are +/- 25 percent compared with nominal.) The study also included an "extremely low" NOAK cost estimate for new nuclear of $2,750/kW. MIT did not define a learning curve, but assumed that utilities will be able to select this NOAK cost option in its modeling. MIT assessed that overnight costs for US reactors could plausibly be reduced by 25–30% percent from its 2009 estimate of $5,000/kW, on account of technological innovations, including advanced fuels, advanced concrete, robotics, and more.

The US Energy Information Administration (EIA) published a report[55] in 2020 that includes overnight costs for advanced nuclear of $6,041/kW and for small modular reactors (SMRs) of $6,191/kW (2019$). According to the Electric Power Research Institute (EPRI), the EIA's National Energy Modeling System (NEMS) assumes cost declines of 5 percent for the first doubling of capacity, cost declines of 3 percent for the next five doublings, and cost declines of 1 percent for any future doublings.[56]

SMR Start, an industry group, looked specifically at SMR deployment by investor-owned utilities and municipal utilities (e.g., the Tennessee Valley Authority, the Utah Associated Municipal Power Systems) in a 2021 paper.[57] It estimated FOAK SMR at $3,800/kW (2020$), and assumed two different learning curves—10 percent and 15 percent—to reach NOAK after 36 reactor modules have been built.[58] NOAK costs are estimated at $2,500/kW and $2,000/kW, for each respective learning curve.

Princeton published a study[59] looking at five different net-zero pathways in the United States. The overnight costs for nuclear were $6,465/kW in 2020, declining to $5,515/kW in 2050 (2016$).

The Breakthrough Institute (BTI) published a study[60] that used two FOAK cost estimates (lower and upper) for four categories of reactors: traditional nuclear ($4,783/kW and $6,338/kW), SMRs ($5,108/kW and $6,974/kW), high-temperature gas reactors (HTGRs) ($5,518/kW and $7,500/kW), and advanced reactors with thermal energy storage ($4,000/kW and $6,220/kW) (2020$). For each technology, the study used two FOAK costs (upper and lower) and then applied two learning curves for later deployments (5 percent and 12 percent, which were cost reductions achieved after a doubling of deployed capacity; no learning was applied to traditional nuclear costs).

The National Renewable Energy Laboratory (NREL) published a study[61] looking at options to achieve 100 percent clean electricity by 2035. The cost assumptions in the core scenario were $6,200/kW in 2020, declining to $5,600/kW by 2035 (2019$). NREL also examined "low-cost" cases where advanced technologies such as SMRs achieve costs of $4,500/kW by 2035.

The Nuclear Innovation Alliance (NIA) organized a workshop on the topic of modeling advanced nuclear energy technologies, and later published a workshop report[62] that recommended modelers use, at a minimum, two representative advanced reactors (e.g., an SMR and an HTGR). For each advanced reactor, NIA recommended using an initial capital cost of $5,550/kW (2020$), which was the midpoint of the estimates reported in its advanced nuclear energy developer survey, the SMR Start study (referenced above), and the BTI study (referenced above). Otherwise, NIA suggested using an initial capital cost within a range of $3,600/kW and $7,500/kW. For future costs assuming growth in cumulative production, NIA recommended using $3,500/kW for year-2050 costs, derived from the same advanced nuclear energy developer study and the SMR Start study, or otherwise assume a cost within $2,000/kW and $5,000/kW. NIA suggested that if the modeling simulated capital cost reduction as a function of capacity deployed, it should assume a learning rate of 5–12 percent, consistent with the BTI report.

A Department of Energy Loans Program Office (LPO) report[63] in 2023 estimated that a "well-executed" FOAK reactor construction project could cost $6,200/kW,[64] though noted that recent FOAK construction projects in the United States have had overnight costs exceeding $10,000/kW. The report assessed that NOAK advanced nuclear overnight costs of $3,600/kW were achievable and might require 10 to 20 reactors deployed in order to reach this target.

An IEA study[65] in 2021 on reaching net zero emissions by 2050 listed NOAK overnight costs used for nuclear reactor builds in various countries and regions (see Table 1).

Table 1: Estimates of overnight costs for NOAK nuclear reactor builds by country/region

Country/region	2020 ($/kW)	2030 ($/kW)	2050 ($/kW)
China	$2,800	$2,800	$2,500
India	$2,800	$2,800	$2,800
United States	$5,000	$4,800	$4,500
European Union	$6,600	$5,100	$4,500

Note: In the IEA report, costs are generally presented in 2019$, though Table B.1, the source of these costs, does not specifically state a year$.

Source: IEA, Net Zero Emissions by 2050: A Roadmap for the Global Energy Sector, 2021, https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroby2050-ARoadmapfortheGlobalEnergySector_CORR.pdf.

Within academic, governmental, and industry estimates for what new reactors will cost, there is substantial variation—greater than a factor of two. Separately, international organizations such as the IEA have assessed the cost of nuclear reactors to vary substantially from one country to another. As the next section explores, these inputs impact modeling of international decarbonization scenarios within the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report.

VI. Nuclear Costs as Found in Integrated Assessment Modeling

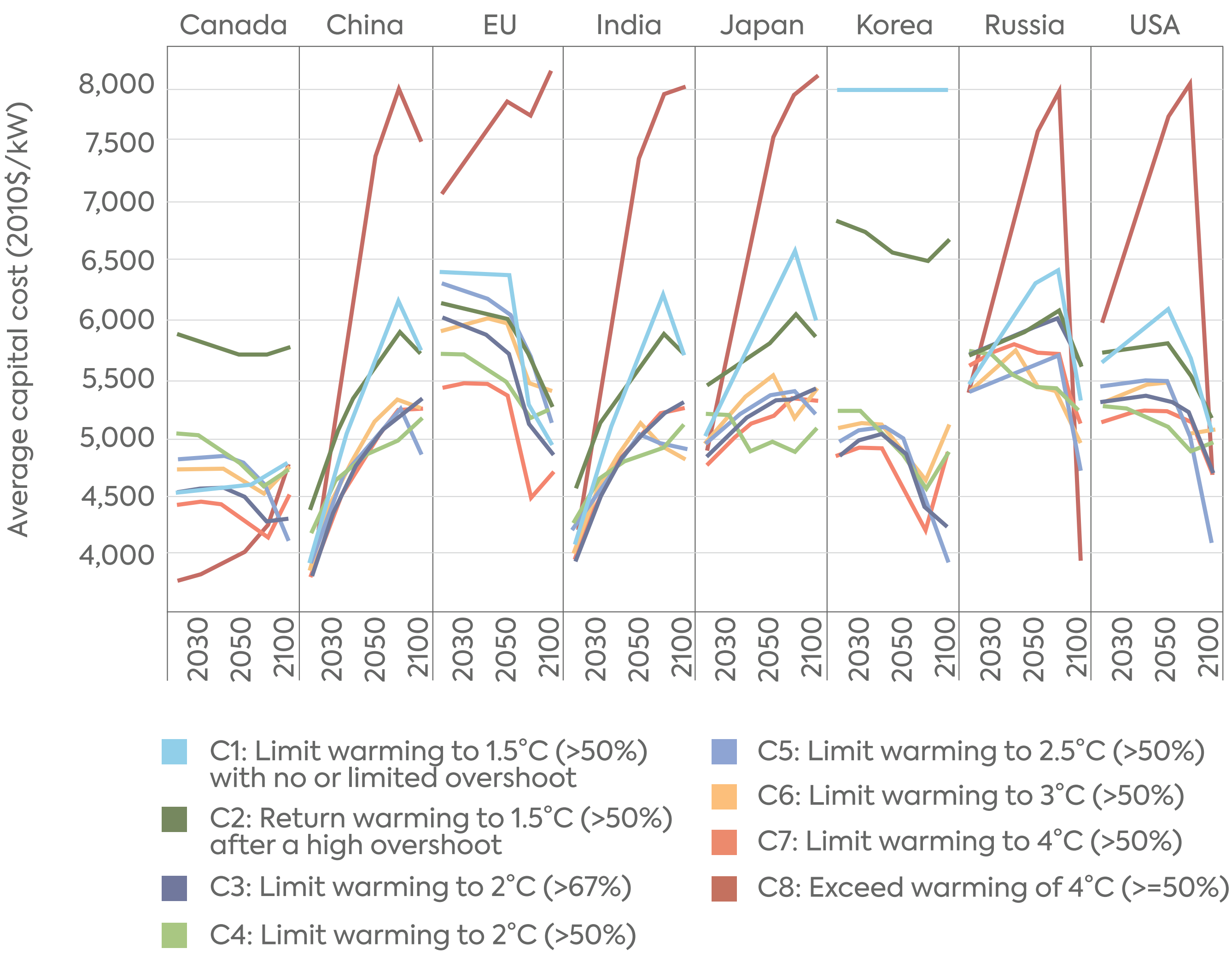
We now move from discussion of nuclear cost input data into energy systems modeling, and turn to a discussion of global integrated assessment modeling (IAM) to incorporate additional insights from the international context and demonstrate the impact of nuclear cost on projected new nuclear installed capacity in climate stabilization scenarios.

Nuclear techno-economic parameters are considered within the IPCC Working Group III scenarios database, and findings from it were included in the recent Sixth Assessment Report, known as AR6. The AR6 scenario database (AR6DB) is transparent and openly available, and enables quantifying the role of nuclear power in various scenarios.[66] AR6DB publishes scenario data relevant to the role of nuclear power in net-zero energy systems globally as well as at the national level beyond the United States. Critically, the AR6DB gathers the quantitative data from leading energy systems modelers within the academic literature, with both national and global modeling focuses. It is a unique, rich, and robust data set to extract global insights from international perspectives on the interaction between nuclear costs and new capacity construction under decarbonization policy scenarios. In general, across international decarbonization studies, greater energy technology learning and nuclear cost reductions are observed in models with more ambitious decarbonization targets and more restrictive carbon budgets.

The IPCC AR6DB reviewed in this study contains decarbonization scenarios in eight categories, C1 to C8. C1 is the most ambitious decarbonization scenario, in which the Paris Agreement goal of staying well below a temperature rise of 1.5°C with limited overshoot is achieved by 2100. Scenario C8 is the opposite end of the spectrum, in which global average temperatures increase by greater than 4°C by 2100.

Figure 3 illustrates the average capital costs (in 2010$) for new nuclear plants in Canada, China, the EU, India, Japan, Korea, Russia, and the US, modeled across different emissions reduction scenarios and pathways. These countries and region were selected because they are the largest energy systems that are consistently available as region definitions within the set of models within the scenarios database. Furthermore, they are also the largest and most polluting energy systems, where the transition to net zero will be significant.

Figure 3: Average nuclear capex costs from IPCC AR6 scenarios for select countries/region and future years



Note: This chart presents data for average values for relevant global regions (Canada, China, the EU, India, Japan, Korea, Russia, and the US) based on relevant nuclear data sets from all 1,200 approved scenarios within the AR6DB. This average trend is shown with the purpose of simple communication to a generalist reader, but it is important to note that this requirement masks the range and diversity of underlying models and socio-technical narratives being run within the models within the AR6DB. The average outcomes for each techno-economic parameter gives a robust trend within a mathematically consistent group of models.

Source: Authors' chart based on AR6DB data.

In general, within scenarios category C8 (red), with low to no decarbonization policy, nuclear capital costs remain high. With little to no incentive to build additional new low-carbon nuclear capacity, the construction learnings and cost reductions do not occur in this scenario category.

Thus costs remain high and new capacity additions are low, unable to compete with other lower-cost electricity sources. Looking at the models' data for each region in sequence, average nuclear capital costs in Canada are stable or gradually declining to mid-century, beyond which nuclear costs are projected to rise across the range of modeled scenario categories. Average capital costs in Canada appear to be the lowest across scenarios and pathways, ranging between $3,840/kW for the warming scenario exceeding 4°C by 2030 and $5,841/kW for a scenario returning temperatures to 1.5°C across 2030, 2050, and 2100 after a high overshoot.

Average capital costs in China, the EU, India, Japan, Russia, and the US rise toward 2050, ranging between $4,361/kW for warming scenarios that limit temperatures to 2.5°C this century to $8,100/kW for scenarios that keep global temperature to 4°C. Note that capital costs reduce in general toward the end of model horizons by 2100 pathways for the C8 scenarios category in these countries, likely because of an uptick in nuclear capacity expansion causing late energy technology learning.

The highest average capital cost across time horizons is found in the C1 scenario in Korea, at $7,980/kW. However, Korea is projected to have the most consistently cheaper new nuclear capacity across the range of scenarios. The model that have a Korea-specific region did not publish a high-emissions C8 scenario into the IPCC database. The GEM-E3 computable general equilibrium (CGE) model, one of the EU commission's integrated assessment models, is the source of this data point and so is not an average across multiple models.

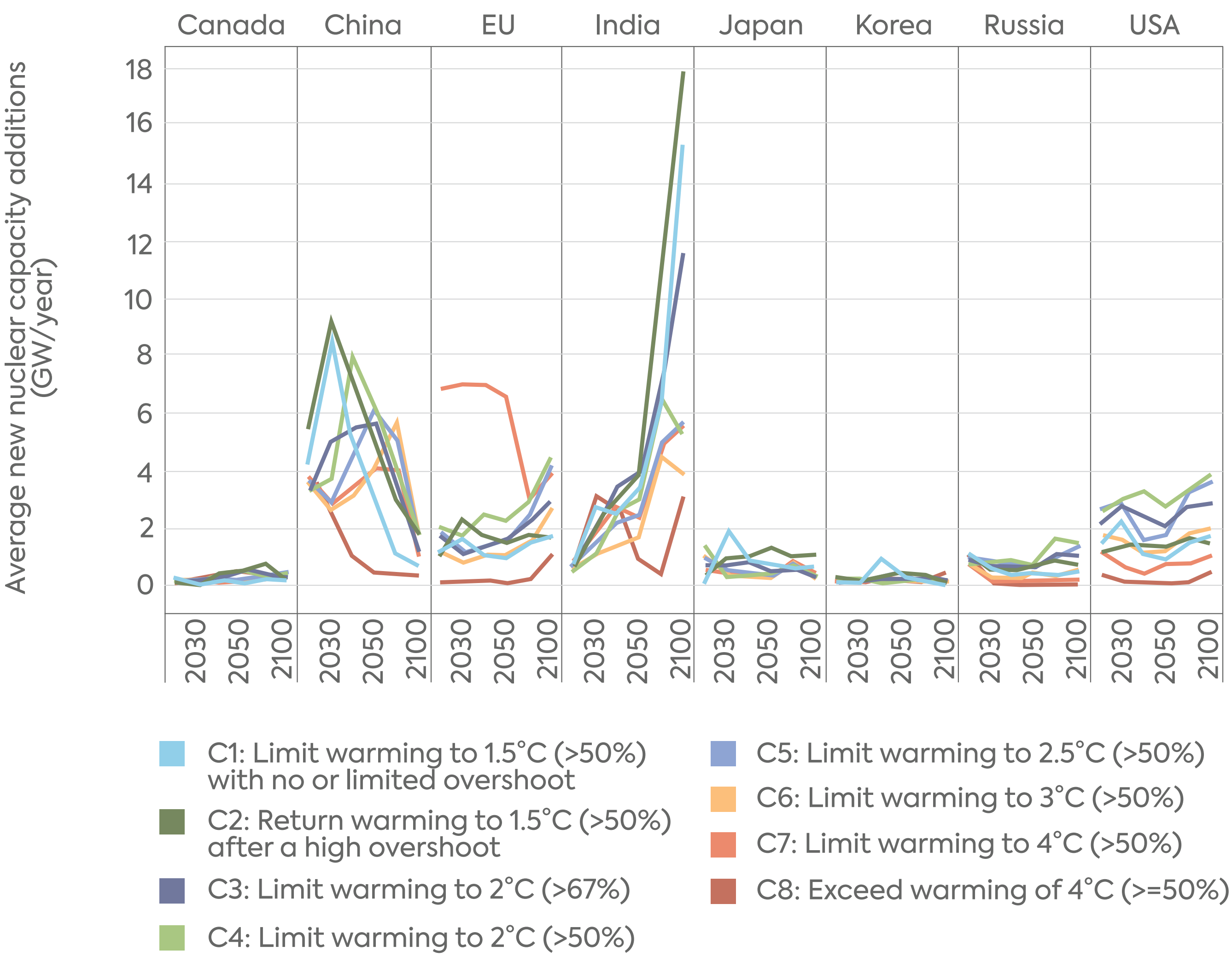
The models indicate that new nuclear capital costs in C1 scenarios, where the climate is stabilized within the Paris Agreement goals, are cheaper than in the C8 Paris Agreement failure scenarios, but are more expensive than in intermediate temperature-rise scenarios. (For the sake of comparison, new nuclear costs are two to four times more expensive per unit capacity than renewable power alternatives built within the AR6DB scenarios.)

Costs for new nuclear builds in IPCC scenarios range between $6,000/kW and $4000/kW in the year 2020 (2010$) for the US and OECD regions, and are broadly in line with the preceding section. Much of the literature and models in the previous section publish their model data into the IPCC database. It is clear to see that emerging economies, such as China and India, still have lower nuclear costs early this century, before wealth (GDP per capita) converges on similar OECD levels by 2050. After this point, there is much less of a cost difference in nuclear costs between OECD and developing regions.

One of the benefits of IAMs and energy systems modeling is the systematic feedback loops built in to their code. One such feedback is energy technology learning. As a technology is deployed and installed capacity of a given technology doubles, the overnight costs decline at a given rate—the endogenous technology learning (ETL) rate. Near-term climate policies drive the near-term acceleration of new nuclear capacity installation in some regions within the IPCC scenarios database. In the scenarios and regions that have significant new nuclear capacity additions, new nuclear capacity additions are relatively cheaper compared to the scenarios and regions without climate stabilization policies. Figure 4 plots the IPCC data illustrating this point and represents the projected annual additions of new nuclear plant capacity in selected relevant regions, across different emissions reduction scenario categories and time horizons.

On average, China is projected to continue to accelerate the growth of annual capacity additions to the order of 6–8 GW per year to 2030–35 in climate stabilization scenarios zwhereby at roughly the same period Chinese CO2 emissions are expected to peak. Beyond 2050 in climate stabilization scenarios, India is projected to take the lead in annual additions of new nuclear capacity in the order of 6–8 GW pear year by 2050 and growing to above 10 GW per year by 2080 in climate stabilization scenarios. India is on average projected to experience the highest annual capacity additions across all mitigation scenarios, time horizons, and emissions reduction categories.

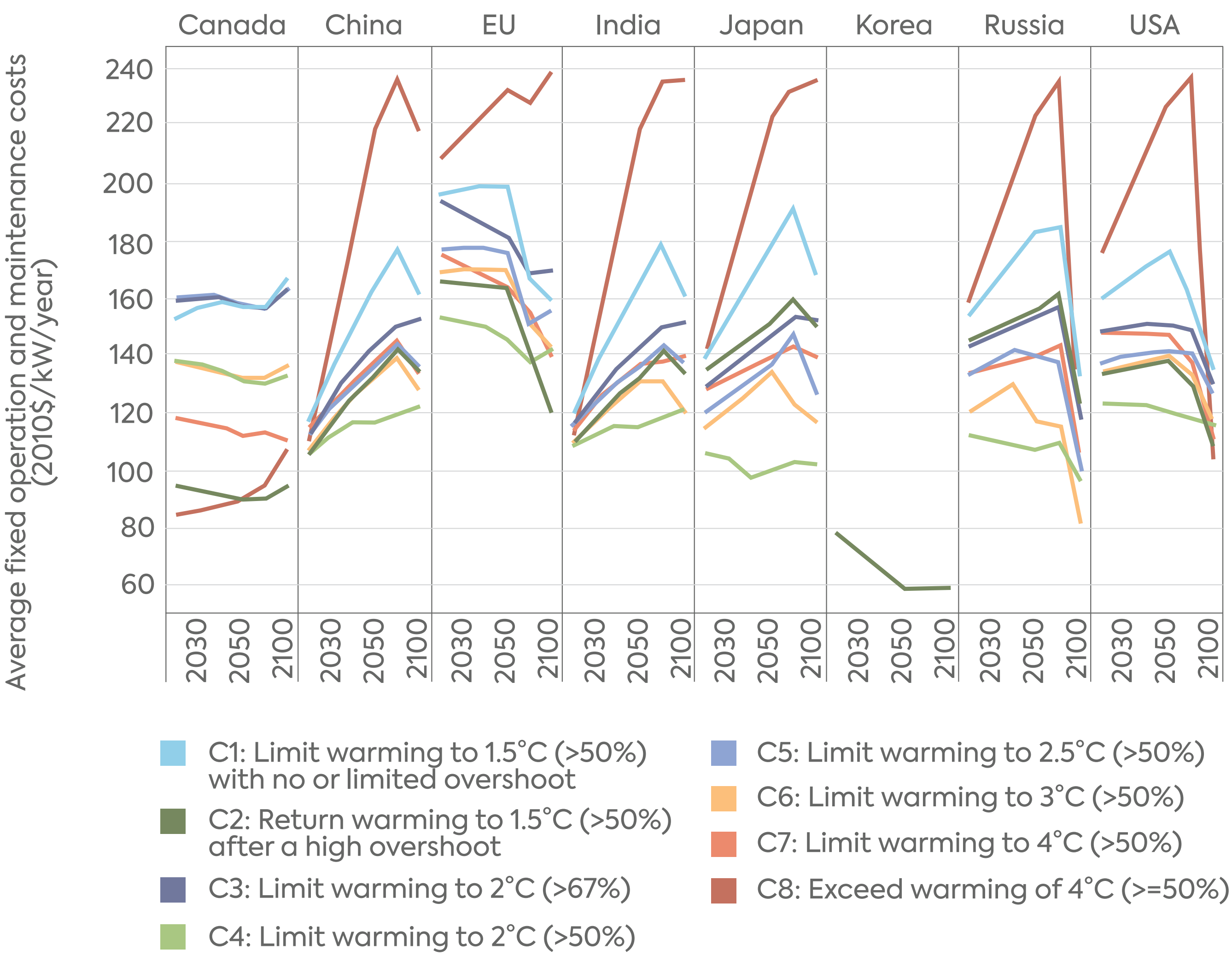
Figure 4: Projected annual additions of new nuclear plant capacity from IPCC AR6 scenarios for select countries/region and future years



Source: Authors' chart based on AR6DB data.

Fixed operation and maintenance (O&M) costs follow similar patterns as capital costs for new nuclear. Figure 5 plots modeled O&M costs for new nuclear plants in the same eight countries/ region explored above and across the same emissions reduction scenarios and pathways.

Figure 5: Average nuclear fixed operation and maintenance costs from IPCC AR6 scenarios for select countries/region and future years



Source: Authors' chart based on AR6DB data.

In general, fixed O&M costs are highest in scenarios category C8, increasing across time horizons with a peak in 2050 and a gradual or sharp decline toward 2100 as a result of declining capital costs encouraged by climate policies, improved learning rate, and economies of scale. Exceptions are Canada and Korea: Canada O&M costs are against the international trend, and we find data only for scenarios category C2 for Korea for this variable.

Across all scenarios (with the exclusion of Korea), average fixed O&M costs are the lowest in Canada, mostly less than $100/kW/year for scenarios category C2 and C8. Aside from scenarios category C8, the highest fixed O&M costs are below $200/kW/year in the other countries and region across time horizons. This is a reflection of the relationship between fixed O&M and capital costs. Fixed O&M costs are usually a percentage of the capital expenditure (capex), so higher capex should translate to higher fixed O&M costs. Similarly, learning by doing in scenarios where increased capacity is built induces learning on construction and operation, often lowering costs.

It is important to note here that one aspect the IPCC's AR6DB scenarios do not explicitly analyze is the potential for SMR and next-generation nuclear reactors to compete with, or more likely complement, variable renewable power generation to provide more reliable baseload capacity, given the intermittency of renewable power capacity. On average, the implication of this caveat is that IAMs can tend to overestimate the role of renewables and underestimate the need for power system flexibility options such as firm power and electricity storage.

Additionally, most models within the IPCC AR6DB do not have the granularity to go beyond economic optimization, to include the real-world unit commitment and capacity expansion technical constraints that may further change the narrative for nuclear power. For such granular analysis, additional modeling is required. However, the IPCC analysis is robust and provides an important insight into the outlook for nuclear power globally. It shows that there is a robust demand for nuclear power in emerging economies with rapidly expanding power systems that are growing and decarbonizing at the same time, with the capacity to build reactors with cheaper overnight costs on a shorter time frame.

VII. Interplay of Costs, Policies, and Competing Technologies on Nuclear's Future

The range of costs for new nuclear has implications for both US and global efforts to decarbonize. In general, lower reactor costs would lead to more nuclear deployment, aiding decarbonization efforts, while higher costs would have the opposite effect.

But as section 4 of this paper discussed, the level of cost reductions that nuclear energy would need to achieve in order to see significant deployment is influenced by several factors, including policy decisions and public support. These factors, as well as advancements in "competing" technologies, will likely affect the scale of new nuclear deployment in the United States, and a number of modeling studies have explored the interplay.

MIT performed electric power modeling of New England and Texas, and found[67] increasing advantages for including new nuclear in the respective systems as limits on carbon emission rates were made more stringent and as nuclear costs were lower. The cost-reduction benefits of nuclear were judged to be higher in New England because the region is less favorable for renewable resources, which means that large amounts of installed renewable capacity and battery storage are required to meet system needs during times of high demand, and substantial battery storage is needed to compensate for weather variability.

NREL modeled four scenarios:[68] (1) all energy technology options continue to see improved cost and performance; (2) transmission technologies improve, and permitting and siting approaches allow greater levels of transmission deployment; (3) constraints are imposed on new generation capacity (including renewable energy and transmission deployment); and (4) CCS technologies do not achieve the cost and performance needed for cost-competitive deployment. NREL estimated there would not be many new nuclear builds in the first two scenarios, but about 40 GW of new nuclear by 2035 when CCS is not competitive, and about 200 GW when renewables and transmission are constrained. In low-cost nuclear sensitivity cases, substantially more new nuclear is built in both of those scenarios.

EPRI convened four modeling teams in 2022 that used national-scale, long-term energy system models from itself, NREL, the EIA, and the US Environmental Protection Agency, which shared methods and data, updated models, ran coordinated scenarios, and identified research needs related to modeling of nuclear energy. The published model intercomparison project (MIP)[69] found a broad range of projected installed nuclear capacity—ranging from 36–92 GW in 2030 and 2–329 GW in 2050 across all policy and technology scenarios. When technology cost assumptions were harmonized across the models, the range of nuclear capacity narrowed to 83–92 GW in 2030 and 63–120 GW in 2050. The study found that greater percentages of nuclear generation occurred in scenarios and regions with favorable: (1) policy conditions, including deeper decarbonization targets and restrictions on other low-emitting options (e.g., CCS); (2) regional economic characteristics, including those with supportive policies for nuclear, as well as perhaps lower wind and solar resource quality; (3) financial assumptions, including lower nuclear capital costs and lower discount rates;[70] and (4) combinations of these factors.

A study[71] by Wesley Cole et al. in 2023 found that five factors could lead to nuclear becoming more competitive: (1) cost reductions for nuclear technologies; (2) stringent carbon emissions limits; (3) limited success in the ability to develop competing low-emission technologies, such as carbon capture and low-carbon hydrogen; (4) limited ability to rapidly deploy renewable energy technologies and transmission; and (5) extensive load growth from electrification. They performed a modeling exercise using the IRA tax credits to determine the amount that new nuclear would need to be cheaper than to reach 50 GW of deployment by 2050. In the reference case, it was $3,000/kW. If siting constraints for new transmission and renewables projects were imposed along with a carbon-free requirement, 50 GW of new nuclear could be competitive at just over $6,000/kW. Requirements for achieving net zero emissions or carbon-free, without the constraints on transmission and renewables projects, indicated that nuclear would need to achieve costs below around $4,300/kW or $4,600/kW.

While these studies were specific to the United States, similar dynamics could exist in other countries.

VIII. Conclusions

Given the checkered history of reactor construction in the US, this may be a make-or-break period for whether nuclear energy expands into a significant player in terms of helping to meet US decarbonization goals. Some other countries have done a better job managing reactor construction and, due to this and other factors (e.g., labor rates), appear able to deploy reactors at lower cost than the US AP1000 and Finnish EPR projects.

Studies reviewed in this paper estimate new US reactor costs generally ranging from $3,000/kW to $6,200/kW (with some higher and lower) based on a variety of reactor designs and cost reduction curves assumed for subsequent years. Internationally, new reactor costs vary significantly by country.

Modeling of nuclear energy costs in the power sector suggests some high-level observations:

- If the costs of new nuclear end up being much higher than some of the upper limits used in the US modeling studies cited, such as above $6,200/kW, new nuclear appears unlikely to play much of a role, if any, in the US power sector.
- In between the cost ranges quoted above, nuclear's ability to play a substantial role in the United States (e.g., the 50 GW of deployment used in Cole et al.) could depend upon factors such as the enactment of stronger decarbonization policies; whether or not other viable firm, low-carbon options emerge as competitive alternatives; continued difficulties with siting new transmission lines; or constraints on renewable energy buildout.
- Internationally, the IPCC scenarios project that lower reactor costs in some emerging countries, such as China and India, in combination with strict climate mitigation policies could result in very large new nuclear capacity expansion.
- Many models within the IPCC international scenarios do not represent power sector operational dynamics, such as unit commitment and dispatch, at the same level of technical completeness as some of the national models referenced in this study. This modeling practice means that, in cases with high variable low-carbon power sources, the need for firm zero-carbon power and storage options can be underestimated, in the absence of greater temporal and technical granularity. This practice can omit costs of flexibility, market reserve, and storage that can be ameliorated by dispatchable nuclear capacity.

Subsequent to the AP1000 project in Georgia, additional data points for new FOAK advanced nuclear power plant costs for the US might not be available until toward the end of this decade or the early 2030s, assuming at least one new power reactor is demonstrated in this time frame. Thus, new nuclear will not meaningfully contribute on the time frame needed to fulfil the 2030 Paris Agreement pledges the US has made. Data on potential cost reductions for any subsequent units would, correspondingly, take years more to emerge.

There is a considerable demand for nuclear power in rapidly growing emerging economies such as China and India. More competitive economics for nuclear in these countries result from lower labor rates, supply chain efficiencies from ongoing nuclear power project buildouts, resultant energy technology learning, and other key factors discussed earlier, which could make them the center of new global nuclear power deployment for the foreseeable future.

What is less clear from the IPCC's AR6DB scenarios is the ability of SMR and next-generation nuclear reactors to compete with variable renewable zero-carbon power. Additional modeling (including site-specific analysis) is needed to go beyond economic optimization to include real-world unit commitment and capacity expansion technical constraints that may further change the narrative for nuclear power.

Notes

1. For example, the International Energy Agency included a near doubling of nuclear power capacity by mid-century in its updated roadmap for net zero emissions by 2050. See International Energy Agency, *World Energy Outlook 2022*, https://www.iea.org/reports/world-energy-outlook-2022.

2. This paper does not look at process heat from reactors for use outside of the power sector, where the economics of decarbonization could be quite different.

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6. See, for example, the testimonies of James Cook, executive editor of *Forbes* at the time, and Gordon Corey, former vice chairman at Commonwealth Edison Company, as part of the 1985 hearings before the Subcommittee on Energy Conservation and Power of the Committee on Energy and Commerce in the US House of Representatives, July 25 and December 10, 1985.

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16. Nuclear Engineering International, "Record Losses for EDF," February 21, 2023, https://www.neimagazine.com/news/newsrecord-losses-for-edf-10612700.

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