Institute for Energy Economics and Financial Analysis

European Pressurized Reactors (EPRs)

Next-generation Design Suffers From Old Problems

Frank Bass, IEEFA Editor

February 2023

Table of Contents

Key Findings

The European Pressurized Reactor (EPR) design has suffered from major cost overruns and schedule delays that aren't improved by subsequent projects.

Only two EPRs are operational, both in China; one was shut down for more than a year because of concerns over damaged fuel rods.

Finland's Olkiluoto 3 EPR was supposed to be online in 2009; its price tag has risen from €3 billion to €11 billion, and the reactor now is expected to go into service in March 2023.

France's Flamanville reactor originally had an estimated €3.3 billion price tag and a 2012 completion date. Costs have risen to €12.7 billion, and fuel loading isn't expected to occur before mid-2023.

Executive Summary

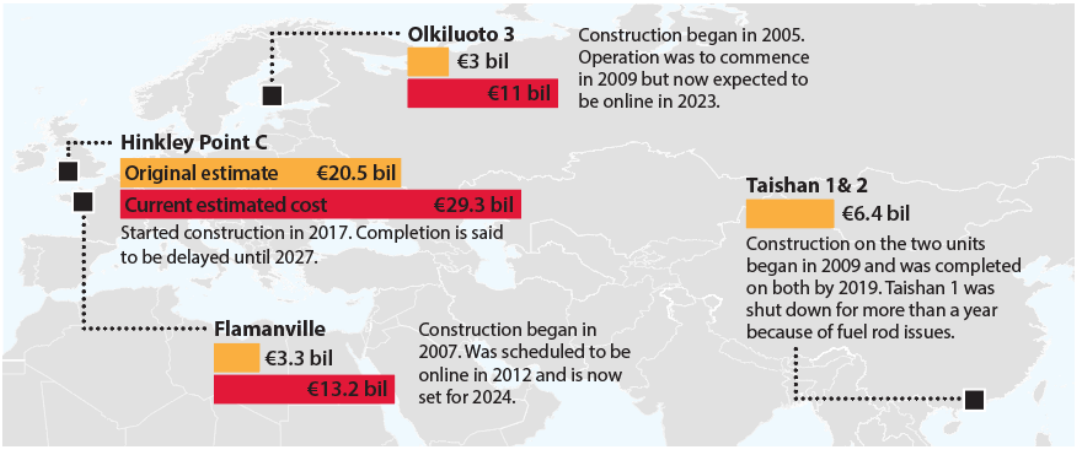
A basic axiom of engineering is that the first product is always the most expensive. As designers and builders gain experience, subsequent products take less time and cost less money than the original product. The newest generation of nuclear reactors, however, is an exception to the rule.

One of the latest iterations of nuclear reactors, the European Pressurized Reactor (EPR), is a prime example of how a promising design has fallen victim to realities on the ground, resulting in massive cost overruns and years-long construction delays.

Five EPRs have either been built or are being built; another one is planned. Four of the five EPRs built have suffered enormous cost overruns and/or significant construction delays. The Taishan 1 reactor in China, the first to be completed, was taken offline in July 2021 because of damaged fuel rods. Two EPRs, the Flamanville reactor in France, and the Olkiluoto 3 reactor in Finland, have been delayed because of operational concerns. The newest reactor to begin construction, the Hinkley Point C reactor in the United Kingdom, after less than four years of construction, is already one-third over its original budgeted estimate and is currently delayed at least two years.

European Pressurized Reactors (EPRs) Suffer Cost Overruns, Delays

A new generation of nuclear reactors known as European Pressurized Reactors (EPRs) suffer from the same issues as other nuclear projects: Massive cost overruns and years of construction delay



The nuclear buildout comes as governments, corporations and individuals struggle to curb emissions from fossil fuels in hopes of limiting global temperature increases to 1.5^{0}C by 2050. The International Atomic Energy Agency (IAEA) predicts that nuclear energy capacity will more than double to 715 gigawatts (GW) by 2050 but still make up no more than 12 percent of global electricity.[1] The small increase in nuclear energy's share reflects the expectation that electricity will be used for a wide variety of activities such as heating and transportation that are currently fueled by carbon-based energy sources. However, it also likely illustrates the cost-effectiveness and increasing popularity of other, faster-growing non-carbon sources of energy, such as solar and wind power.

With an anticipated lifespan of 60 to 80 years, nuclear energy has advantages over solar and wind (25 years) and natural gas-fired facilities (30 years). However, overnight construction costs for nuclear energy—the amount of money it would take to build a facility without interest being charged—are much higher than most other sources. A study by the U.S. Energy Information Administration (EIA) pegged the typical overnight cost of a nuclear reactor at USD$6,695 per kilowatt (kW), which compared extremely unfavorably to USD$1,718/kW for onshore wind, USD$4,833 for offshore wind, and USD$1,748 for a solar-plus-storage project.[2]

Moreover, the costs of wind and solar have been plummeting, and are expected to continue to decline, while nuclear construction costs, especially in the United States, have risen sharply. Utility-scale solar fell 88 percent between 2010 and 2021;[3] the average cost of land-based, wind-driven energy has fallen 68 percent since 2010.[4] The costs of nuclear energy, meanwhile, rose almost 33 percent between 2015 and 2020.[5]

The problems with EPR reactors cast the nuclear dilemma into sharp relief. Nuclear energy may be part of the climate change solution, but among its other pitfalls, it is a very expensive alternative to renewables. And as the costs of renewable energy sources continue to fall,

[1] International Atomic Energy Agency. Energy, Electricity and Nuclear Power Estimates for the Period up to 2050. September 16, 2021.
[2] U.S. Energy Information Administration. Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2022. March 2022.
[3] International Renewable Energy Agency. Renewable Power Generation Costs in 2021. July 2022.
[4] *Ibid.*
[5] PV Magazine. 'Nuclear power is now the most expensive form of generation, except for gas peaking plants'. September 24, 2020.

nuclear facilities that have cost investors and ratepayers billions face a very real risk of becoming stranded assets well before the end of their projected lifespans.

Introduction

The news about new nuclear power designs keeps getting worse. The European Pressurized Reactor design, once hailed as an improved method of building safer, more efficient nuclear plants on time and under budget, is instead the centerpiece of troubled facilities around the planet that are years behind schedule, billions over their original estimated cost, or suffering significant operational problems.

The most recent EPR setback occurred in mid-December, when state-owned French utility Électricité de France (EDF) announced that its Flamanville EPR reactor on the Cotentin Peninsula will now cost €13.2 billion, a €500 million increase, and will open six months later than planned due to the need to study heat treatment methods on welds.[6]

The issues with the French reactor occurred barely a month after Finnish operator Teollisuuden Voima (TVO) announced that the Olkiluoto 3 EPR reactor—which has been under construction since 2005 and was planned to be in service in early 2009[7]—won't be fully online until early March 2023 because of damage to feedwater pumps at the Baltic Sea facility.[8]

The pressure vessel holding the reactor core for a third EPR, the Hinkley Point C plant on the west coast of the United Kingdom, was completed in mid-December. Project costs, however, have risen to at least €28 billion, €9 billion over its original estimate, and its anticipated completion date of 2025 has slid by two years.

An EPR reactor in China was completed in December 2018, but the Taishan 1 reactor in Guangdong was taken offline in July 2021 because of damaged fuel rods.[9] The unit, one of the

[6] Reuters. EDF announces new delay for Flamanville EPR reactor. December 16, 2022.
[7] World Nuclear News. TVO receives further shareholder loan commitment. December 17, 2020.
[8] YLE. Testing resumes at Finland's newest nuclear reactor. December 27, 2022.
[9] World Nuclear News. Chinese EPR experiences 'performance issue.' June 14, 2021.

first two finished by China General Nuclear Power Group (CGNPG) and part-owned by EDF, didn't re-enter service until August 2022.

The problems with the EPRs underscore the challenges related to relying on new designs (and nuclear power in general) to replace fossil fuels in a timely and cost-effective manner. Although nuclear power provides almost 20 percent of electricity in the United States,[10] concerns persist about its costs and safety. Cheaper and safer alternatives, such as wind and solar, have led at least three countries—Italy, Kazakhstan and Lithuania—to abandon their nuclear ambitions.[11] The track record suggests that more of the 33 countries with nuclear power facilities should consider following their lead and seek out safer and more cost-effective energy sources.[12]

EPRs: An Overview

The EPR is not new; it's a third-generation pressurized water reactor (PWR) designed by EDF, Siemens and Areva. The reactor was created to improve safety and increase efficiency, with costs at least 10 percent lower than coal-fired plants.

The EPR design features four independent cooling systems; enhanced reactor containment; an exterior shell that contains a molten core; and a two-layer, eight-and-one-half foot concrete wall strong enough to withstand a military or commercial aircraft from breaching the reactor.[13]

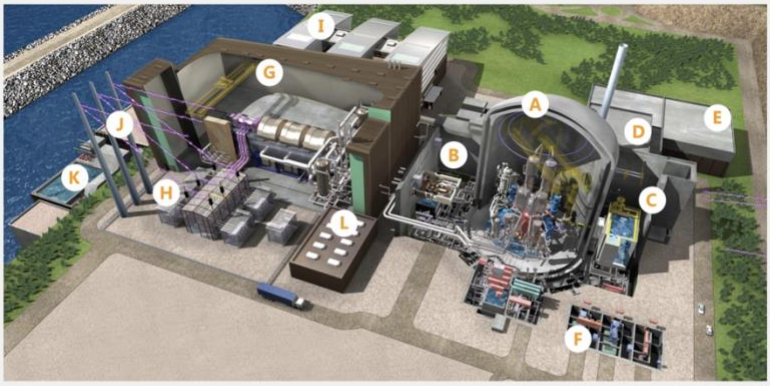
Nuclear reactors produce electricity using nuclear fission to superheat water, creating steam that drives turbines. Following the same basic method, the EPR is designed to produce 1.6GW of electricity. In addition, they include a core surrounded by a neutron reflector to improve efficiency and prevent the pressure vessel from prematurely aging because of radiation; they have fewer welds than traditional reactors and high-quality steam generators that increase efficiency.[14]

[10] U.S. Department of Energy. Nuclear. Accessed December 19, 2022.
[11] Mycle Schneider. World Nuclear Industry Status Report, 2022. October 2022.
[12] World Economic Forum. Which countries have the most nuclear reactors? October 27, 2022.
[13] Framatome. The European Pressurized Water Reactor: A Safe and Competitive Solution for Future Energy Needs. September 6, 2004.
[14] *Ibid.*

Nuclear energy has been touted as one of the planet's best options for diminishing reliance on fossil fuels and meeting the International Energy Agency (IEA) goal of reaching a net-zero energy economy by 2050 that would limit global temperature increases to below 1.5^{0}C.[15] Yet given the history of nuclear fission—high costs and potentially cataclysmic effects, such as those experienced in Hiroshima, Nagasaki, Chernobyl and Fukushima—concerns remain about the safety and impact of nuclear projects. Critics have raised concerns that there is insufficient time to build safe and reliable nuclear plants between now and 2050. Initial planning between EDF and major German utilities for the EPR began as far back as 1992.[16] The first reactor, the Taishan 1 unit in the southern Chinese province of Guangdong, however, didn't enter commercial service until 2018, more than a quarter-century later.

There are real concerns about the costs of new nuclear designs. Even existing nuclear plants with older designs carry heavy price tags. A 2021 Lazard analysis found nuclear energy costs were between $131 and $204 per megawatt-hour (MWh); the costs of utility-scale solar ranged between $28 and $37/MWh, and the price of wind between $26 and $50/MWh.[17] The IEA estimates that annual investments in clean energy will need to more than triple by 2030 to $4 trillion annually for the planet to limit temperature increases to 1.5^{0}C—a goal that's unlikely to be met

Figure 1: European Pressurized Reactor Design



Source: EDF Energy.

[15] International Energy Agency. Net Zero by 2050. May 2021.
[16] Nuclear Engineering and Design. The European pressurized water reactor: Result of the French-German cooperation of experienced NPP suppliers and operators. January 1999.
[17] Lazard. Levelized Cost Of Energy, Levelized Cost Of Storage, and Levelized Cost Of Hydrogen. October 28, 2021.

using unproven and costly technologies that are out of financial reach for most of the world's population.[18]

The EPR design has three competitors: The AP1000 by Westinghouse, VVER-1200 in Russia, and Hualong One in China.[19] Issues, particularly surrounding costs, have recently been identified with each. Problems with the EPR design, however, have been well understood since 2010, when a French government report noted:

"The complexity of the EPR comes from design choices, notably of the power level, containment, core catcher and redundancy of systems. It is certainly a handicap for its construction, and its cost. These elements can partly explain the difficulties encountered in Finland or Flamanville."[20]

France: Flamanville

Although the United States has more nuclear reactors than any other country in the world, France is the largest per-capita consumer of nuclear power.[21] Areva began building the Flamanville reactor on the English Channel in late 2007. EDF predicted it would begin commercial operations in 2012 and carry a €3.3 billion price tag. Costs and delays have risen steadily since work began on the 1.6GW project.

By 2012, EDF announced that costs had risen to €8.5 billion and the project would not be completed until 2016, due to engineering and design changes, as well as the need to address safety issues in the wake of the 2011 Fukushima nuclear disaster.[22]

Construction was delayed in November 2014 because of delays in the delivery of components, and again in April 2015 when problems were discovered with the steel used in the reactor

[18] International Energy Agency, *op. cit.*
[19] Reuters. Explainer: What happened at China's Taishan nuclear reactor? June 15, 2021.
[20] Francois Roussely. The future of the French civil nuclear programme. 2011.
[21] Raymond Murray and Keith Holbert. *Nuclear Energy: An Introduction to the Concepts, Systems, and Applications of Nuclear Processes, Eighth Edition*. Oxford: Butterworth-Heinemann, 2020.
[22] Reuters. EDF raises French EPR reactor cost to over $11 billion. December 3, 2012.

vessel.[23] Additional questions about the safety of the French nuclear program were raised by the February 2017 fire and explosion in a turbine adjacent to one of the Flamanville facility's two existing pressurized water reactors.[24]

A blistering October 2019 government audit of the Flamanville project highlighted poor planning and coordination, describing it as a "failure for France's entire electricity and nuclear sector."[25] EDF blamed ensuing delays on the 2020 outbreak of the COVID-19 pandemic, repairs on penetration welds on the reactor building and damaged fuel rods.[26]

The latest delay was announced in December 2022, with EDF conceding that it would need another six months and €500 million to ensure that the welds would be strong enough to hold when the reactor was brought online.[27] The project's estimated costs are now €12.7 billion, and fuel loading is not expected to occur before the second quarter of 2023.[28]

Finland: Olkiluoto 3

The Olkiluoto 3 reactor is considered especially vital to Finland since the country receives about 15 percent of its electricity through Russia, which cut off supplies after the traditionally neutral Nordic nation asked to join NATO in the wake of Russia's invasion of Ukraine.[29] Currently, the Olkiluoto 3 reactor is 13 years behind schedule, and its price tag has risen from €3 billion to €11 billion.[30]

TVO, the plant operator majority owned by Pohjolan Voima Oy (Northern Power Co.), applied to build the 1.6GW reactor in 2000. Work began in 2005. The project was troubled from the start. A concrete base was laid incorrectly, and the steel liner that would be used to contain any radioactive release suffered from welding issues. A 2006 report by the Finnish Radiation and

[23] The Local. Flamanville fiasco: The story of France's nuclear calamity. February 9, 2017.
[24] BBC. Flamanville reactor blast: No nuclear risk, say officials. February 9, 2017.
[25] Reuters. France orders EDF to tackle nuclear project failings. October 28, 2019.
[26] World Nuclear News. Fresh delay to Flamanville 3 blamed on pandemic. January 12, 2022.
[27] Reuters. EDF announces new delay for Flamanville EPR reactor. December 16, 2022.
[28] Reuters. EDF hopeful end in sight for long-delayed, budget-busting nuclear plant. June 16, 2022.
[29] The Associated Press. Russia has cut off its natural gas exports to Finland in a symbolic move. May 21, 2022.
[30] YLE. Olkiluoto 3 reactor plugged into national grid, 13 years behind schedule. December 3, 2021.

Nuclear Safety Authority Subcontractors responsible for much of the construction had no experience building nuclear facilities, and regulators questioned the project's safety culture.[31]

A 2013 delay that pushed the anticipated completion date back to 2017 was blamed on the failure to obtain regulatory approval for the unit's instrumentation and control (I&C) equipment from regulators, although the Areva-Siemens consortium building the plant blamed the failure on TVO.[32] The 2013 announcement was followed by a 2017 acknowledgement by TVO that more tests were needed, and commercial operations would not begin until mid-2019.[33]

The repeated delays forced Areva (now known as Framatome and majority-owned by EDF), to pay €450 million to TVO in arbitration as compensation for delays in 2018.[34] The reactor achieved criticality in December 2021,[35] and the facility reached full power in September 2022.[36] Issues were discovered with the unit's feedwater pumps in November 2022, however, and TVO estimates production will not resume until late January.[37]

China: Taishan 1 and 2

China General Nuclear Power Group (CGNPG) signed a deal with EDF in 2007 to build two 1,750MW EPRs at Taishan, a city of almost 1 million in Guangdong. Construction on the reactors, which are 70 percent owned by CGNPG, began in 2009, with a targeted completion date of 2014. The first unit, however, wasn't finished until late 2018. The second reactor began operations about a year later.[38]

In its first year of operation, the Taishan Unit 1 reactor recorded 428 hours of unplanned shutdowns because of "human factors," possibly attributable to a lack of worker training.[39] The

[31] STUK. Management of Safety Requirements in Subcontracting During the Olkiluoto 3 Nuclear Power Plant Construction Phase. January 9, 2006.
[32] New York Times. Finnish Nuclear Plant Won't Open Until 2016. February 11, 2013.
[33] Reuters. Areva's Finland reactor to start in 2019 after another delay. October 9, 2017.
[34] Metropolitan. Teollisuuden Voima (TVO) confirms Areva to pay 450 MEUR for Olkiluoto 3 (OL3) Nuclear Power Plant delays. March 11, 2018.
[35] Reuters. Finland's long-delayed Olkiluoto 3 reactor to come on stream in Jan. December 16, 2021.
[36] TVO. Olkiluoto 3 at full power for the first time. September 30, 2022.
[37] Agence France Presse. Production At New Finnish Nuclear Plant Delayed To January. November 21, 2022.
[38] Framatome. Framatome welcomes the commercial start-up of the second EPR reactor. September 7, 2019.
[39] Hong Kong Free Press. Factwire: Records show 'human factors' caused 428 hours of unplanned shutdowns in Chinese nuclear reactor's first year. November 6, 2021.

reactor was the subject of a June 2021 U.S. investigation after Framatome, the EDF subsidiary that designed the reactor, warned that it was facing "an imminent radiological threat."[40] The CGNPG was placed on a U.S. blacklist in 2019 for attempts to acquire advanced nuclear technology for military uses; Framatome, which has U.S. operations, required a waiver from the U.S. government to allow it to help fix CGNPG technology issues.[41]

EDF, CGNPG, and U.S. officials said the problem, which involved a buildup of inert gases in the reactor, posed no major issues. The Chinese Ministry of Ecology and Environment said even with damaged fuel rods, the plant was "operating safely and within standards and no abnormalities have been found in the surrounding environment."[42]

The ministry claimed that five fuel rods were damaged; a whistleblower in the French nuclear energy industry, however, claimed as many as 70 of the reactor's 60,000 fuel rods were damaged, possibly because of design flaws.[43] Despite protests that the incident was blown out of proportion by media reports, the unit was shut down for more than a year, and only reconnected to the grid in August 2022.[44]

United Kingdom: Hinkley Point C

The UK approved the Hinkley Point C EPR project in 2012—but only after three other designs were withdrawn.[45] The UK government guaranteed the EDF a price of £92.50 per MWh, tied to inflation over 35 years for the two 1.6GW reactors at Hinkley Point, even though the wholesale price at the time was £40 per MWh.[46] The terms were so favorable to the French company that the European Commission launched a 2013 inquiry into the deal, concerned that it could affect other projects throughout Europe.[47] The commission ultimately gave its stamp of approval in late

[40] CNN. Exclusive: US assessing reported leak at Chinese nuclear power facility. June 14, 2021.
[41] Reuters. Explainer: What happened at China's Taishan nuclear reactor? June 15, 2021.
[42] China Daily. Taishan nuclear plant operating safely, with no leak. June 16, 2021.
[43] The Diplomat. Safety Concerns Mount Over Damaged Fuel Rods at China's Taishan Nuclear Plant. December 11, 2021.
[44] Nuclear News. Taishan-1 EPR resumes operation a year after shutting down over reactor damage fears. August 25, 2022.
[45] BBC. New nuclear plant, Hinkley Point C, design unveiled. December 13, 2012.
[46] The Guardian. Hinkley Point: the 'dreadful deal' behind the world's most expensive power plant. December 21, 2017.
[47] The Guardian. European commission inquiry into Hinkley Point deal could delay project. December 2, 2013.

2014 but noted that the project would wind up costing at least £24 billion and not be completed until 2024.[48]

The French government, meanwhile, saw the project as an opportunity to market the EPR design and boost EDF's sagging balance sheet. It promised a financial bailout in early 2016 to the state-owned utility to ensure that the Hinkley Point project proceeded.[49] The UK government postponed a final investment decision on the £18 billion project in mid-2016, even as EDF and CGNPG, which owned a one-third stake in the project, prepared to sign contracts.[50]

The deal was finally approved in September 2016;[51] less than one year later, EDF acknowledged the project was £1.5 billion over budget and a year behind schedule.[52] As early as 2017, the project was derided as "a failed and failing reactor" and "a dreadful deal, laughable" for UK consumers.[53] The cost rose another £2.9 billion in late 2019 because of issues with moving ground at the site.[54] The COVID-19 pandemic was responsible for another yearlong delay announced in May 2022; EDF said the reactor would not begin operating until June 2027 and would cost at least £25 billion to complete.[55]

Conclusion

Cost overruns and delays at one nuclear reactor site could be written off as an aberration. If the history of the industry teaches us anything, however, it is that building a nuclear reactor *always* entails cost overruns and delays.

[48] The Guardian. EU approves Hinkley Point nuclear power station as costs raise by £8bn. October 8, 2014.
[49] The Guardian. France agrees bailout for EDF to proceed with Hinkley Point C. March 17, 2016.
[50] The Guardian. Hinkley Point C in doubt after British government delays approval. July 29, 2016.
[51] The Guardian. Hinkley Point: ministers sign go-ahead for nuclear power plant. September 29, 2016.
[52] The Guardian. Hinkley Point C is £1.5bn over budget and a year behind schedule, EDF admits. July 3, 2017.
[53] The Guardian. Hinkley Point: the 'dreadful deal' behind the world's most expensive power plant. December 21, 2017.
[54] The Guardian. Hinkley Point nuclear plant building costs rise by up to £2.9bn. September 25, 2019.
[55] The Guardian. Boss of Hinkley Point C blames pandemic disruption for £3bn delay. May 20, 2022.

Consider, for example, the Westinghouse AP1000 design being built at Southern Company's Plant Vogtle site in Georgia. The price of the reactors was originally estimated at $14 billion; costs have now soared past $30 billion, and the schedule has slid by more than six years.[56]

Another new design, NuScale's small modular reactor (SMR) that was originally estimated to cost $5.3 billion, promised a 36-month construction window, prices of $58 per MWh, and a 95 percent operational capacity—a trifecta that has never been accomplished by a U.S. nuclear plant. The company recently announced costs would rise to $9.3 billion, a 75 percent increase, and prices would rise to $89 per MWh. The NuScale project, which has been in development since 2000, would not begin commercial operations before 2029 at the earliest.[57]

A review of EPR projects shows there's no single quick fix for the reactors. Each of the four EPR reactors that have been built or are being built have unique problems. The issues with the feedwater pumps at Olikuoto; fuel rods at Taishan; earth-moving at Hinkley Point; and welds at Flamanville point to larger issues that will take considerable amounts of time and money to resolve.

Despite the EPR problems, France—which nationalized EDF in 2022—is doubling down on its nuclear plans. President Emmanuel Macron asked for 14 new nuclear reactors last year, even as more than half of the country's 56 reactors were idled for maintenance, drought or repair.[58] EDF, for its part, continues to push its EPR design in Poland (unsuccessfully),[59] as well as Slovakia and India, where it has a tentative approval to build six of the reactors.[60]

It is difficult to imagine that building more EPR reactors will result in anything but blown timelines and bloated budgets. A 2020 Massachusetts Institute of Technology study found that successive iterations of a new nuclear design frequently cost more than the original facility; the EPR design, in other words, is unlikely to become cheaper as more units are built.[61] There is neither sufficient

[56] IEEFA. Southern Company's Troubled Plant Vogtle Nuclear Project. January 2022.
[57] IEEFA. NuScale's Small Modular Reactor. February 2022.
[58] France 24. France outlines plans for buyout of EDF to relaunch country's nuclear industry. July 19, 2022.
[59] Nuclear Engineering International. EDF reaffirms its commitment to supporting Polish nuclear power programme. November 10, 2022.
[60] The New Indian Express. India and France discuss ways to speed up the building of world's largest nuclear site. October 19, 2022.
[61] Greentech Media. MIT Study Lays Bare Why Nuclear Costs Keep Rising. December 8, 2020.

time nor capital to resolve the multiple problems with the EPRs, and cheaper, safer alternatives exist. The EPR reactors represent sunk costs—spending billions more on an unproven design would represent a sunk cost fallacy, or the idea that spending more money eventually will fix the problem. Utilities, investors and government decision makers should move past sunk costs and focus on relatively low-cost, carbon-free technologies with falling price tags that work, rather than expensive and unproven megaprojects.

About IEEFA

The Institute for Energy Economics and Financial Analysis (IEEFA) examines issues related to energy markets, trends and policies. The Institute's mission is to accelerate the transition to a diverse, sustainable and profitable energy economy. www.ieefa.org

About the Author

Frank Bass

Frank Bass is the U.S./Canada/Europe editor for IEEFA. He is a Pulitzer Prize-winning reporter and editor whose career has focused on the intersection of government, politics and business, with particular attention to the energy industry. He is currently a graduate degree student at the University of Alaska Fairbanks, majoring in Arctic and Northern Studies.