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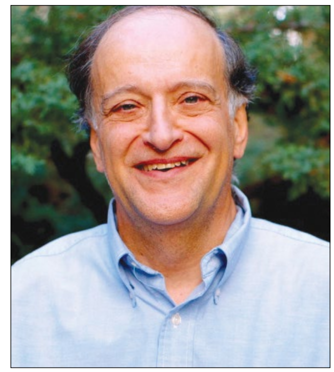
Prominent in this issue is the announcement of the winners of the 2023 Forum awards. As you are aware of, the Forum yearly gives out two prizes: the Burton and Szilard awards. The winners this year are respectively Richard Meserve and Laura Grego and they well deserve our congratulations. Details of their accomplishments are given in the News section of this issue.

We have also in this issue two articles: one is on the possible (or impossible) contribution of nuclear energy to solving the global warming problem. No doubt some people will agree and some disagree with the author's point of view and I look forward to publishing articles and letters to the Editor on this topic. The other article has an update on the possibility of generating power via fusion instead of fission

We have also a letter to the Editor and our usual complement of book reviews, now under the charge of our new Book Review editor.

I remind you again that the contents of this newsletter **are largely** reader driven. Go ahead and send your contributions and your suggestions. All topics related to Physics and Society, very broadly understood, are welcome. **No pertinent subject needs to be avoided, certainly not on the grounds of controversy, which I welcome.** Content is **not peer reviewed and opinions given are the author's only, not necessarily mine, nor the Forum's nor, *a fortiori*, the APS's either.** Letters to the Editor for publication are also welcome.



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Every contribution should be sent to me, preferably in.docx format, except Book Reviews which should be sent directly to book reviews editor Quinn Campagna (qcampagn@go.olemiss.edu).

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Infeasible: Nuclear Energy as a solution to Climate Change

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Nuclear energy reached a major landmark in 2021. Its share of the total electrical energy generated globally declined to below 10 percent, 9.8 percent to be precise (1). That fraction is lower than it has been since at least 1985, and around 45 percent lower than its peak in 1996, when nuclear energy provided 17.5 percent of worldwide electricity fed into the grid. The declining trend has been continuous and will likely continue.

The declining trend might seem odd given all the talk one hears about nuclear energy undergoing yet another "renaissance" or "resurgence" (2–4). Although such claims were always questionable (5–7), they have propelled enormous amounts of public and private capital going into nuclear power. Further, this trend would seem doubly odd in the face of high-profile assertions about the inevitability of nuclear energy to mitigating carbon emissions (8–10).

The key reason for the decline in the share of nuclear power is economical: generating power with nuclear reactors is costly compared with other low-carbon sources of energy, and the gap is widening. The second reason for this decline is the very long time it takes to build a nuclear reactor.

Combined, these two trends imply that nuclear energy will not help solve climate change. For nuclear energy to play a significant role in mitigating climate change, its share of the electrical energy produced around the world has to necessarily increase, as fossil fuels are replaced by uranium. And the shift has to occur rapidly. Nuclear energy is simply not up to this challenge.

There is a separate and well-known set of reasons about why nuclear power is not a desirable way to even trying to mitigate climate change: the unavoidable risk of severe accidents, the inextricable connection to nuclear weapons proliferation, and the inevitable production of hazardous radioactive waste. Since nuclear power is incapable of contributing significantly to mitigating climate change, expanding nuclear energy and exacerbating these undesirable outcomes makes no sense.

THE ECONOMICS OF NUCLEAR POWER

Despite countries around the world investing vast amounts of money in nuclear power, the technology continues to be economically uncompetitive. Two separate cost problems afflict nuclear power. First, nuclear reactors are extremely expensive to build. The Vogtle nuclear plant being built in the state of Georgia, involving two AP1000 reactors designed to generate around 1,100 megawatts of electricity each, is currently estimated to cost nearly $35 billion (11,12). In 2011, when the utility building the reactor sought permission from the Nuclear Regulatory Commission, it projected a total cost of $14 billion, and “in-service dates of 2016 and 2017” for the two units (13).

As of March 2023, neither unit has started operating. Westinghouse, the company developing the design, originally projected a time period of three years to construct each AP1000 reactor (14). Vogtle has exceeded that projection by a factor of three.

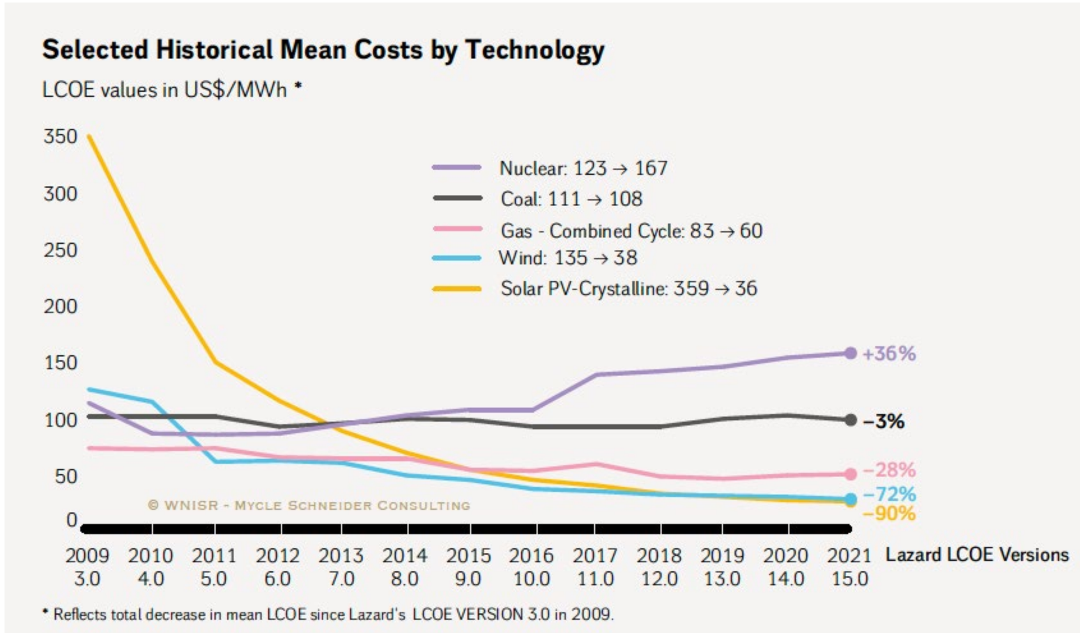
Vogtle is by no means the only delayed reactor. In Finland, building of the Olkiluoto-3 European Pressurized reactor (EPR) started in August 2005; its builders expected it to start operating in 2009, but it was first connected to the grid only in 2022, a thirteen year delay (15). The story of its sister EPR at Flamanville in France is similar. Although its construction started two years later—and presumably the builders had some time to learn from the experience in Finland—that reactor is now expected to start operations in 2024, a dozen years after the expected 2012 (16). Like Vogtle, its cost has escalated dramatically, from €3.2 billion to €13.2 billion.

These construction delays are occurring in United States, which has built more reactors than any other country, and France, which has the highest nuclear share in the world. In other words, these problems are not being encountered by some neophyte country embarking on building its first nuclear power plant.

There is no reason to expect things will get better in the future. Historical experience in the United States and France shows that nuclear construction costs have typically gone up, not down, as more reactors are built (17–20). Cost estimates of the European Pressurized reactors being built at Hinkley Point in the United Kingdom are greater than the costs of the Flamanville and Olkiluoto reactors; the estimated costs of the Russian VVER reactors proposed for Turkey and Bangladesh are higher than the cost of the first two Koodankulam reactors operating in India.

The second cost problem afflicting nuclear power involve the high operating expenses of nuclear reactors. These expenses do not include what is involved in servicing the extremely high capital costs, and yet are high enough to make nuclear energy uncompetitive with natural gas, solar, and wind power.

Over the last decade or so, this second cost problem has forced utilities to shut down multiple old reactors despite having active operating licenses (21–24). In the United States, 104 nuclear reactors were operating at the end of 2010 (25). A decade later, in December 2020, that was down to 94 (26). The number of operating reactors declined from 19 to 15 in the United Kingdom; and from 10 to 6 reactors in Sweden. The nuclear fleet would be even smaller but for governments shoveling exorbitant subsidies at utilities owning nuclear plants, partly due to misguided beliefs about the importance of nuclear power for mitigating climate change. But an equally important reason has been lobbying by the nuclear industry and its supporters, as well as systemic corruption (27,28).



Plot of trends in the cost of generating electricity (the so-called Levelized Cost of Energy) from the 2022 World Nuclear Industry Status Report (1) which is based on cost estimates reported by the Wall Street advisory firm Lazard from 2009 to 2021.

Nuclear power's economic challenge is graphically shown in the figure above, which is drawn using data presented in successive cost reports by the Wall Street advisory firm Lazard (29,1). At nearly $170 per megawatt-hour of electricity, generating nuclear power costs over four times the corresponding figure for utility-scale solar and wind farms.

The comparison between nuclear power and variable renewables like solar and wind is complicated by the fact that the latter sources do not generate power steadily, and depend on how much wind is blowing and whether the sun is shining. But the very large cost differential between nuclear and renewables should be more than enough to allow for complementary technologies to compensate for variations in the outputs of solar and wind farms (30). There is also a vast literature that explores how renewables can support a reliable electrical grid provided suitable and affordable options, such as energy efficiency, demand response, technological and geographic diversity, and some storage, are incorporated (31).

THE QUESTION OF TIME

Nuclear reactors are not just expensive. They take a very long time to construct. The average nuclear plant takes around a decade to go from when the first concrete is poured on the ground to the first units of power flowing into the grid (1). The requisite planning, getting permits, and raising the billions of dollars in funding needed to construct a plant, might take up to a decade too.

Consider the case of Hinkley Point C in the United Kingdom where two EPRs are being built at Hinkley Point. In 2008, the U.K. government issued a White Paper that envisioned new reactors producing power by 2018, further recommending Hinkley Point as where the first nuclear plant could be built because it already had the requisite environmental clearances (32). In reality, it was December 2018 by the time the first of the two EPRs began to be built at Hinkley Point C; the second unit started being built in December 2019. The currently projected start date for the first of the reactors is 2027, with the cost estimate of the two EPR units touching $40 billion (33).

This is the case in the United Kingdom, which is very familiar with this process. Over the decades, the country has built 45 power reactors. Experience with nuclear power is not an advantage that many other countries have.

Although many propose to expand nuclear power to combat climate change, few discuss where these new nuclear plants are to be built. For nuclear power to contribute significantly to mitigating climate change, much of this new nuclear capacity would have to be built in developing countries. These are the countries that have fast expanding energy needs and growing populations. But, few developing countries use nuclear energy.

One of the few attempts at identifying a potential geographical distribution of new nuclear reactors was the influential study published by the Massachusetts Institute of Technology (MIT) in 2003 (34). The MIT study developed a scenario where nuclear power contributes significantly to mitigating climate change by 2050 and came up with a hypothetical allocation of new nuclear power plants to countries around the world.

That scenario foresaw a number of countries like Algeria, Indonesia, Malaysia, North Korea, the Philippines, Venezuela, and Vietnam all acquiring their first nuclear power plants by

2050. Indonesia, for example, would have to build up 39 gigawatts of nuclear capacity by 2050. To reach that target, Indonesia should build around 25 large nuclear reactors like the ones at Hinkley Point C or 35 reactors like the ones at Vogtle. Today, two decades after the MIT report came out, Indonesia still has no operating nuclear power plant; nor is one being built.

There is a good reason why developing countries, despite a desire to build nuclear capacity, have not built nuclear power plants in large numbers. Financial resources for capital intensive projects are scarce in cash-strapped developing countries, and nuclear plants are prohibitively expensive. Nor should these countries be considering nuclear power, for it is an expensive and inefficient way to deliver energy to the developing world's unserved people.

Despite these reasons for foreswearing nuclear technology, perhaps many developing countries might develop nuclear power plants after all. But that is unrealistic within the next few decades. In April 2022, the Intergovernmental Panel on Climate Change stated that "global temperature will stabilise when carbon dioxide emissions reach net zero. For 1.5°C (2.7°F), this means achieving net zero carbon dioxide emissions globally in the early 2050s" (35).

In other words, to meet the goals of the Paris Agreement, the world has to stop emitting carbon dioxide, or find ways of absorbing the emitted carbon dioxide, within three decades. Nuclear power's track record and technical constraints make it clear that it cannot play any significant role in reaching this target.

CAN NEW SMALL MODULAR NUCLEAR REACTOR DESIGNS HELP?

When faced with these facts, some proponents of nuclear energy argue that alternate nuclear reactor designs will solve the problems confronting nuclear power. A particular focus has been on what are called Small Modular (Nuclear) Reactors (SMRs). SMR designs typically have power levels between 10 and 300 megawatts, much smaller than the 1,000–1,600 megawatt reactor designs being built today (36).

Nuclear proponents also talk about so-called advanced reactors, or Generation IV nuclear energy systems, which are based on designs not involving cooling by water: such designs include gas-cooled high temperature reactors, sodium cooled fast neutron reactors, and molten salt reactors cooled by, well, molten salts. Many of these reactor designs also fit into the category of small modular reactors because they are intended to produce less than 300 megawatts.

First, let us discuss SMRs. Because SMRs produce less power, nuclear advocates expect building these would cost less. Therefore, in principle, smaller private companies and countries with smaller economic capacity (i.e., GDP) can invest in nuclear power. While the lower total cost may help deal with the first problem, the second problem becomes worse because small reactors lose out on economies of scale.

Larger reactors are cheaper on a per megawatt basis because their material and work requirements do not scale linearly with power capacity. A general rule of thumb followed in industrial engineering postulates a 0.6 power relation between the capital cost and the size of the facility (37). All else being equal, constructing a SMR designed to produce 200 megawatts would cost around 40 percent of what it would cost to build a 1000 megawatt reactor, whereas it would generate only 20 percent of the electricity. Thus, the 200 megawatt SMR would have roughly twice the cost per kilowatt of capacity, which directly translates into a higher cost per unit of electricity generated.

Cost estimates of SMRs under development offer evidence of higher per kW costs. The UAMPS project involving six NuScale units proposed to be built in Idaho is estimated to cost an eye-popping $9.3 billion for just 462 megawatts of power capacity (38). That amounts to over $20,000 per kilowatt. In comparison to the Vogtle project in Georgia, when that project was at a comparable stage—that is, when it was still on paper—the estimate for the UAMPS project is around 250% more than the initial per kilowatt cost of the Vogtle project. Of course, the Vogtle cost has since exploded, but there is every reason to expect a similar fate for the UAMPS project if and when construction starts. Even without such an increase during construction, the NuScale SMR design is more expensive than large reactors on a per kilowatt basis.

SMR proponents have a counter argument: the lost economies of scale will be compensated by savings through mass manufacture in factories and resultant learning. But, for the price per kilowatt for a small reactor to be comparable to large reactors, SMRs have to be manufactured by the hundreds, maybe thousands, even under very optimistic assumptions about rates of learning (36). If and when all those SMRs are manufactured, then, perhaps, the cost per kilowatt of SMRs might match the cost per kilowatt of large nuclear reactors. Even then, SMRs will only economically competitive with the likes of the Vogtle nuclear plant, and generate power at costs that are many times that of renewable sources of energy.

Even that sombre outlook might be too optimistic for the real world where multiple theoretical assumptions made by SMR developers will not hold. For example, they assume that costs of nuclear power plants will decline as more of these are built; but, in both the United States and France, costs rose with time (19,20). The theoretical prerequisite for such learning is that most reactor builders would choose a standardised design. But there are currently dozens of SMR designs being developed around the world. This makes it very unlikely that one, or even a few designs, will be chosen by different countries and private companies.

Building SMRs has also been subject to delays. Russia's first SMR is the KLT-40S, which is based on the design of reactors used in the nuclear-powered icebreakers operated by

Russia for decades. When construction started in 2007, the KLT-40S reactor was expected to start operating in October 2010. It began producing power a whole decade later, in May 2020 (39).

Even in the case of designs being developed, there are significant delays. NuScale, the design closest to being deployed in the United States, has gone from planning to first generate power in 2015-16 to the current expectation that the first reactor will start producing power in 2029-30 (40)

Turning to the so-called advanced reactor designs, there is a long history of reactor designs not based on standard light-water-reactor technology being built around the world. And this history shows that these designs will have a number of technical problems that make them unreliable for electricity generation (41,42).

When it was established in 2000, the Generation IV initiative's aimed for "commercial deployment by 2020–2030" (43). In 2018, the Generation IV forum concluded that "readiness for commercial fleet deployment" might occur only "around 2045 (for the first systems)" (44). The delay should not come as a surprise: these designs are challenged by major technological problems. In 2015, France's Institut de Radioprotection et de Sûreté Nucléaire (IRSN) examined these challenges, concluding that "the SFR [Sodium-cooled Fast Reactor] system [is] the only one of the various nuclear systems considered by GIF [Generation IV International Forum] to have reached a degree of maturity compatible with the construction of a Generation IV reactor prototype during the first half of the 21st century; such a realization, however, requires the completion of studies and technological developments mostly already identified" (45).

But even sodium-cooled fast reactors are unlikely to be built quickly, and there is a long history of delays, poor performance, and nagging problems afflicting these designs (46). India's Prototype Fast Breeder Reactor (PFBR) offers an illustration of the lengthy delays associated with even new sodium cooled reactor designs. The government started planning to building the PFBR in the early 1980s, after a quarter century of dreaming about breeder reactors (47). In 2004, when the first concrete was poured, the PFBR was expected to start operating in 2010. The reactor has been delayed repeatedly and is now expected to start operating in 2024 (48).

The bottom line is that new reactor designs, whether these are termed small modular reactors or advanced reactors or Generation IV reactors, cannot help nuclear power be deployed fast enough to meet the urgency of climate change mitigation.

CONCLUSION

Nearly a quarter century ago, the physicist Freeman Dyson wrote, "the characteristic feature of an ideologically driven technology is that it is not allowed to fail. And that is why nuclear energy got into trouble. The ideology said that nuclear energy must win. The promoters of nuclear energy believed as a matter of faith that it would be safe and clean and cheap and a blessing to humanity. When evidence to the contrary emerged, the promoters found ways to ignore the evidence" (49).

Dyson's characterization of nuclear power's promoters holds till today. Nuclear advocates continue to ignore the evidence for the decline in importance of nuclear energy and its inability to compete economically with renewable sources of energy. New reactor designs will not rescue nuclear power from this fate.

The climate crisis is urgent. The world has neither the financial resources or the luxury of time to expand nuclear power. In the 2019 issue of the *World Nuclear Industry Status Report*, Amory Lovins, another physicist, expressed this idea succinctly: "to protect the climate, we must abate the most carbon at the least cost—and in the least time—*so we must pay attention to carbon, cost, and time, not to carbon alone*" (50).

From the perspective of minimizing cost and time, expanding nuclear energy only makes the climate problem worse. First, the money invested in nuclear energy would save far more carbon dioxide if it were invested in further the switch to renewables. There is thus an economic opportunity cost to investing in nuclear energy. And the long timescales involved in expanding nuclear power means that the reduction in emissions from alternative investments would not only be greater, but also quicker.

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Inertial Fusion Energy Basic Research Needs Summary

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In 2022, DOE Office of Fusion Energy Sciences (FES) commissioned a Basic Research Needs (BRN) report in Inertial Fusion Energy (IFE) to identify the main priority research opportunities (PROs) in IFE that can be supported by a newly established IFE program within FES. In addition, the DOE charge for the BRN called for a Technology Readiness Assessment of the different IFE concepts, an evaluation of the magnetic fusion energy (MFE) efforts that could be leveraged to advance IFE, and an assessment of the private sector role in a national IFE Program. The ultimate goal is to develop a path toward a viable IFE fusion pilot plant (FPP). A fusion pilot plant is an integrated fusion energy system with the primary goal to produce electricity from fusion and demonstrate critical performance metrics to enable first-of-a-kind commercial fusion power plants. [NAS report 2018]

The demonstration of ignition in the laboratory has long been considered as a critical milestone for initiating a coordinated program aimed at developing inertial fusion energy (IFE) as stated in the 2013 U.S. National Academy of Sciences report on IFE: "In the event that ignition is achieved on the National Ignition Facility or another facility, and assuming that there is a federal commitment to establish a national inertial fusion energy R&D program, the Department of Energy should develop plans to administer such a national program (including both science and technology research) through a single program office." The urgency to establish an IFE program is further augmented by the rapidly growing interest shown by the private sector to engage in the development of fusion energy. A summit of fusion technology leaders from the public and private sectors was hosted by the White House Office of Science and Technology Policy in March 2022 to develop a decadal vision for commercial fusion energy. Private funding for fusion has skyrocketed in the last decade and surpassed $4.7B, with $180M going into IFE in the last two years. Establishing and growing a national IFE program while partnering with private industry could fast-track the development path for fusion energy.

An integrated IFE program will necessarily include many different science areas, technology development efforts, infrastructure needs, private industry involvement and workforce recruitment. To provide comprehensive guidance, PROs were developed at a wide-ranging level (Overarching PROs) as well as at each area-specific level (Focused PROs). Additional guidance is provided in the form of Structural Concepts that could benefit the development of a new IFE program at its inception.

FINDINGS

1. IFE is a promising approach to fusion energy with different technical risks and benefits with respect to MFE. It can be an important part of the FES R&D portfolio.

2. The recent demonstration of the threshold of thermonuclear ignition on the National Ignition Facility constitutes a pivotal point in the development of inertial fusion energy.

3. Major advances in IFE-relevant physics and technology, including demonstration of the threshold of ignition, occurred over the last several decades funded mostly under the national security mission. The U.S. is the recognized leader in IFE science and technology because of this investment.

4. Private industry is driving the commercialization of fusion energy in the U.S., and public-private partnerships could greatly accelerate the development of all fusion energy concepts.