US nuclear power: The vanishing low-carbon wedge

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Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved May 30, 2018 (received for review March 20, 2018)

Nuclear power holds the potential to make a significant contribution to decarbonizing the US energy system. Whether it could do so in its current form is a critical question: Existing large light water reactors in the United States are under economic pressure from low natural gas prices, and some have already closed. Moreover, because of their great cost and complexity, it appears most unlikely that any new large plants will be built over the next several decades. While advanced reactor designs are sometimes held up as a potential solution to nuclear power's challenges, our assessment of the advanced fission enterprise suggests that no US design will be commercialized before midcentury. That leaves factory-manufactured, light water small modular reactors (SMRs) as the only option that might be deployed at significant scale in the climate-critical period of the next several decades. We have systematically investigated how a domestic market could develop to support that industry over the next several decades and, in the absence of a dramatic change in the policy environment, have been unable to make a convincing case. Achieving deep decarbonization of the energy system will require a portfolio of every available technology and strategy we can muster. It should be a source of profound concern for all who care about climate change that, for entirely predictable and resolvable reasons, the United States appears set to virtually lose nuclear power, and thus a wedge of reliable and low-carbon energy, over the next few decades.

decarbonization | nuclear power | wedges | SMRs

The need to mitigate emissions of global warming gases is critical. Once carbon dioxide enters the atmosphere, more than a third of it remains there, causing warming for hundreds of years (1), a fact that few Americans recognize (2). Despite this lack of awareness and the current absence of political will to address climate change, technological improvements, continuing political pressure, and a growing familiarity with adverse climate effects will likely result in the United States decarbonizing its energy system to some extent over the coming decades. However, to come anywhere close to meeting the targets enshrined in the Paris Agreement of limiting temperature increases to "well below 2 °C above preindustrial levels" (3), the United States and the world as a whole are going to have to achieve drastic emission cuts, and perhaps even negative emissions, in the next several decades (4, 5).

It has been widely argued that the most plausible and cost-effective strategy to achieve deep decarbonization is by deploying a portfolio of "everything we've got." Given the myriad technical, economic, and political constraints that challenge the deployment of all energy infrastructure, relying on a large number of different technologies and strategies, executed in parallel, would reduce overall costs and risks (6, 7), with each one of these contributing a "wedge" to the overall mitigation effort (8). Indeed, most models of decarbonization incorporate a large suite of technologies and assume that they are deployable when the political will to mitigate emissions emerges.

Nuclear power is one of those technologies. For several years, we have been evaluating the potential role that new nuclear power technologies might play in this decarbonization by conducting a variety of studies that investigate the technical, economic, and political challenges that face it, both in the United States and around the world. We have concluded that, barring some dramatic policy changes, it is most unlikely that nuclear power will be able to contribute to decarbonization in the United States, much less provide a new carbon-free wedge on the critical time scale of the next several decades. With the exception

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Author contributions: M.G.M., A.A., M.J.F., and M.R. performed research and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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of a few other nations, including China, the same may also be true across the rest of the world.

The Existing US Nuclear Fleet Is Shrinking

For three decades, roughly 20% of US electric power generation has come from large light water nuclear reactors (LWRs) (9) that were developed at the beginning of the atomic age. Because of low natural gas costs, these facilities are no longer the cash cows they were only a decade ago. Moreover, an increase in the penetration of renewable energy sources has turned nuclear reactors into mid-merit generators. Combined, these two phenomena have made operating smaller, older reactors cost-prohibitive. As a result, the United States is in the midst of a series of shutdowns of LWRs that will take ∼10 GW_e of reliable, low-carbon capacity offline (10–12). The states of New York, Illinois, and New Jersey have adopted policies to avert a small number of these shutdowns (13, 14), but this will only slow, not reverse, the losses.

Even if the immediate economic pressures on existing nuclear power plants are reduced, the existing plants are aging. "Life extension," the effect of running them for 60 or 80 years on the structural integrity of their components, is the subject of intense research. Even if they are deemed safe, extending their useful lives further will require expensive refurbishment and careful regulatory consideration. Thus, for example, while continued availability of some nuclear power could considerably ease California's commitment to decarbonizing its energy system (15), these and other factors, including public opposition to nuclear power, are resulting in the phase-out of all of the state's nuclear plants (16, 17).

Because constructing new nuclear power plants takes so long, the time to decide whether and how to embark on a new program to build nuclear power plants in this country is upon us. Replacing retiring units with new ones is not easy. Recent efforts to kickstart nuclear construction in the United States have failed. Construction of two Westinghouse AP1000s at the Virgil C. Summer plant in South Carolina was abandoned last year. Although the project was only 40% complete, it had already cost $9 billion (18). Southern Nuclear's efforts to build two of the same reactors at its Vogtle plant in Georgia are continuing, but the company currently expects the project to cost approximately $25 billion, a staggering $11,000 per kW_e, and these costs are expected to rise (19). Duke Energy recently cancelled plans to build a new nuclear plant in Florida (20).

There is no reason to believe that any utility in the United States will build a new large reactor in the foreseeable future. These reactors have proven unaffordable and economically uncompetitive. In the few markets with the will to build them, they have proven to be unconstructible. The combination of political instruments and market developments that would render them attractive, such as investment and production credits, robust carbon pricing, and high natural gas costs, is unlikely to materialize soon.

If nuclear power is to survive as a viable commercial option in the United States, the industry needs to move away from large LWRs and toward either smaller reactors or a different technology that reduces or eliminates the challenges associated with large LWR designs. We have analyzed the benefits and risks of these two options and discuss both in the sections below.

Advanced US Designs Will Not Be Available for Many Decades

Proponents of nuclear power have long argued that advanced designs, especially non-light water reactor designs, could make a major contribution to deep decarbonization. Indeed, traditional LWRs were only meant to constitute the first generation of nuclear power plants, and sober analysts in the 1970s expected the United States to have a fleet of advanced reactors by the turn of the century (21). While some of these advanced designs promise innovations that could make reactors cheaper and safer, and material control more manageable, these benefits remain speculative.

The steward for nuclear innovation in the United States is the Department of Energy's (DOE) Office of Nuclear Energy (NE). One of its major missions has been to develop advanced non-light water reactors. In fact, its current vision is for at least two of these designs to be ready for commercial deployment by the early 2030s; in other words, they would have reached "technical maturity, demonstrated safety and economic benefits, and completed licensing reviews by the US Nuclear Regulatory Commission" (22). Using budget data acquired through the Freedom of Information Act and semistructured interviews with 30 senior nuclear energy experts, we recently analyzed the DOE's efforts to commercialize advanced reactor designs (23, 24). NE has spent $2 billion on this effort since the late 1990s, with very little to show for it. This is unsurprising: Even by its own assessment, this amount is less than half what is necessary to demonstrate even one non-light water technology. Moreover, NE's spending portfolio conflicts with much of the wisdom regarding the execution of innovative research and development programs: Annual funding varies fourfold, priorities are erratic, and spending on existing infrastructure (some of which is obsolete or ill-suited to support testing of new designs) consumes more than half of the budget. Moreover, the funds dedicated to advanced reactors have been spread across a number of different designs and fuel types, not because a conscious choice has been made to further these technologies based on their technical, economic, and institutional benefits but because they are the favored projects of different national laboratories (23, 24). In interviews with leaders across the enterprise, those associated with the DOE and the national laboratories expressed either alarm or despair at the trajectory of advanced fission innovation in the United States (24).

Often, proponents of nuclear power note that private enterprise is faring better than the government at advancing non-light water reactor concepts. Indeed, more than $1.3 billion has been secured by close to four dozen such companies (25). However, a dozen of these are working not on advanced fission reactors but on fusion reactors or nuclear fuels. Another dozen reactors either belong to bankrupt companies (e.g., Westinghouse) or are proceeding at a very low level of activity (e.g., the DOE's Next Generation Nuclear Plant and various university ventures that are very much in the conceptual design phase). Moreover, while $1.3 billion sounds impressive, that sum is dominated by one firm, TerraPower, which has found it remarkably challenging to build or secure access to the range of equipment, materials, and technology required to successfully commercialize its innovative design (26). As a result, it is teaming with China in its development efforts.

Our analysis suggests that in order for advanced nuclear technologies to play a role in deep decarbonization over the next several decades, more competent stewardship of nuclear innovation, substantially greater appropriations, and a change in energy markets, all very heavy lifts, will be required (23, 24).

The Fading Promise of Factory-Built Small Modular Reactors

If large reactors constitute "bet the company" investments and advanced US designs are unlikely to emerge, the only remaining course of action by which the domestic nuclear industry could contribute a "carbon-free wedge" in the near term is to develop and deploy smaller light water reactors. These small modular reactors (SMRs) are quite attractive in theory, and their primary innovation is their smaller size. Not only would each module cost a fraction of what a large reactor would in absolute terms but the small size would also allow vendors to fabricate these in much the same way as other large, complex technologies, such as airliners and turbines. It would also allow utilities to deploy these low-carbon generators in smaller increments depending on how much demand growth they project, how much base load generation their portfolios require, and how carbon policy evolves. Moreover, the small size enables secondary innovations in safety, siting, construction, and deployment.

Because light water technologies are the only ones that can rapidly (i.e., within the next decade) clear the technical and regulatory hurdles that challenge the development of new nuclear technologies, a number of firms have designed light water SMRs, and one has already submitted its design certification application to the US Nuclear Regulatory Commission (27). NuScale Power is planning to deploy its first power modules at the Idaho National Laboratories, and the DOE has supported the reactor's development and expressed interest in both securing a purchase agreement for a portion of the power generated and potentially using one or two of the modules for testing purposes. Since the DOE granted NuScale a site use permit for Idaho in 2016, 18 other vendors have approached the laboratory to explore the possibility of also siting their first units on its grounds (28).

Through a combination of engineering economic analysis and the use of structured procedures to elicit expert judgments, we have evaluated the likely cost and performance of deploying these light water SMRs for the provision of electric power (29). Our results reveal that while one light water SMR module would indeed cost much less than a large LWR, it is highly likely that the cost per unit of power will be higher. In other words, light water SMRs do make nuclear power more affordable but not necessarily more economically competitive for electric power generation. That vision of the dramatic cost reduction that SMR proponents describe is unlikely to materialize with this first generation of light water SMRs, even at *n*th-of-a-kind deployment.

Because light water SMRs incur both this economic premium and the considerable regulatory burden associated with any nuclear reactor, we do not see a clear path forward for the United States to deploy sufficient numbers of SMRs in the electric power sector to make a significant contribution to greenhouse gas mitigation by the middle of this century. Nevertheless, we have expended much effort in developing plausible scenarios of how an SMR domestic market might develop. These revolve around niche markets and nonelectric applications. Here, we discuss three such applications that are often presented as especially promising: first, deploying SMRs as a source of low-carbon process heat for industrial applications; second, switching SMRs back and forth between electric generation and water desalination to complement intermittent generation from renewable energy sources; and third, deploying these reactors as a highly reliable and independent source of electrical and thermal energy for US military bases. We have also performed an assessment of the potential global market for SMRs, focusing on the impact of national institutions on the safe and secure deployment of mass-produced reactors.

Using Light Water SMRs to Provide Industrial Process Heat. We began by evaluating the likely cost and performance of deploying light water SMRs in facilities across the United States that require substantial amounts of industrial process heat. After building a database that summarized the features and process needs of more than 5,000 facilities, including refineries, petrochemical plants, metal and glass manufacturers, pulp and paper mills, and cement kilns, it became clear that, to first order, there exists a substantial potential market for SMRs in this space. Indeed, our analysis suggests that this market could theoretically host perhaps 1,000 small reactors, and potentially up to 4,000, depending on both their size and the assumptions made about the processes at these facilities.*

Three states with extensive industrial capacity would have to host a third of these reactors: Texas, Louisiana, and California, with Texas alone accounting for ~20% of the potential national market. As expected, industrial powerhouses in the Midwest and South offer substantial markets as well. These states include Iowa, Illinois, Ohio, Indiana, Alabama, Pennsylvania, and Michigan. Alaska also figures prominently.

Despite this large potential, our analysis reveals four major challenges. First is the cost: Once we compare the economics of using light water SMRs to supply process heat instead of natural gas, the number of potential customers falls precipitously. In fact, it becomes cost-prohibitive to deploy reactors across entire industries, such as refineries. This is especially true in high-temperature applications where light water SMRs would support electric heating. Second is construction financing: Very few corporations have a financial profile that supports such a large investment in a substitute technology, especially before it attains *n*th-of-a-kind costs and reliable performance and in the absence of stringent carbon policy. Even in the South, where nuclear construction is conceivable, industrial consumers of process heat are likely to be more apprehensive than electric power utilities since they lack the latter's ability to pass on the risk of cost growth to their customers. A third challenge is the large number of regulatory and siting issues that neither reactor designers nor regulators have resolved yet. A range of issues, including emergency planning in the presence of many potentially hazardous effluents, would have to be resolved before this market would be sufficiently appealing to warrant SMR deployment. Finally, there exist operational challenges: light water SMRs with outlet temperatures of 320–350 °C can cater to many industrial markets, but not to those that demand high-temperature heat unless these reactors are supplemented with electric heating, which is possible but capital-intensive. Using this market to justify the development of a program of factory SMR production appears to be a particularly implausible strategy, given industry demands for cheap heat, predictable performance, and low commercial risk: When it comes time to sign contracts and pour concrete, it is highly unlikely that any industrial customer would opt for a light water SMR, let alone at first-of-a-kind.

Hybrid Power and Desalination Systems. Another potential market application we have explored is the use of SMRs to desalinate water. Operationally, SMRs can leverage desalination in several ways. Of course, it is possible to dedicate modules entirely to desalination if water supplies become scarce; however, this is only likely to happen in some regions. In addition, we have explored a hybrid model. As the United States adds ever larger amounts of variable and intermittent renewable energy sources to the electric power system, storage will become increasingly

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*Abdulla A (2018) Evaluating the potential role of nuclear power in decarbonizing the industrial process heat sector (School of Global Policy and Strategy, University of California, San Diego).

important. Unlike electricity, which cannot be easily stored, water is both strategically valuable and extremely easy to store. Hence, an interesting application for SMRs might be a system that produces electric power when wind and solar resources are either unavailable or poorer than forecast [in the case of wind, these droughts can last for days (30)] and desalinates water when there is ample output from renewable energy facilities. It is important to recognize that this system could take the form of either an SMR or any baseload, low-carbon energy source, including natural gas plants fitted with carbon capture and sequestration (CCS) technologies.

There is, of course, uncertainty about what either system would cost. Our modeling suggests that the cost of doing this using natural gas with CCS stochastically dominates the cost of doing it with a light water SMR. The median cost of the system using natural gas with CCS is ∼80% of the cost of the SMR alternative. Even if the SMR system could be made more cost-competitive, the commercial and perceived safety risks of doing this with natural gas are clearly much lower than those for a nuclear system.[†]

Unlike most commodities, it is very difficult to determine the cost of water in the more arid parts of the United States because supplies have been heavily subsidized by government-funded infrastructure. In addition, complex water laws often allocate significant amounts of water to lower value uses, such as agriculture. However, there is some history of transactions in which urban areas have arranged to purchase water from entities that own water rights. While the data are spotty, when we construct a distribution of payments that have been made for such transactions, it falls well below the distribution of our cost estimates for the desalination systems under investigation. In fact, the median cost estimate is just 15% of the cost of the system that uses natural gas with CCS.

While we knew that the water supply situation is not uniform across the United States, we had initially expected there to be a number of markets where desalination might be necessary in the near to medium term. Upon closer investigation, there appear to be very few niche markets, such as West Texas and the Monterey Peninsula, where supply may become a serious issue in the next few decades. The global picture is different, of course, and there are regions, including the Middle East, South America, and Southern Africa, where the market for desalination is larger. However, as we discuss below, the United States is unlikely to be able to develop a viable SMR industry primarily on the basis of export markets.

Leveraging the US Military to Accelerate SMR Development. Because it is unlikely that further and substantial DOE funding will be dedicated to reinvigorating civilian nuclear power, and because the nuclear enterprise is unlikely to rebound on its own, some have advanced national security arguments to stem and reverse the perceived decline in US standing by assigning this task to the Department of Defense (DoD). Given the current political climate, which supports American primacy in areas of strategic importance, supporters in Congress, think tanks, the Army, and the Navy have floated the possibility of diverting large sums of money through the DoD to catalyze the development and deployment of SMR technologies (31–35).

While we share the fears about the future of nuclear science and nuclear power in the United States, we believe that the proposal to try to address the problem through DoD leadership in development is both unwise and unlikely to succeed. There are several practical challenges. Any SMR that is designed to primarily serve the DoD would likely be too expensive for a commercial utility to deploy. The design specifications upon which the DoD would insist would likely render commercial variants infeasible (because, to minimize or avoid frequent refueling, it would likely need to use fuel that is enriched more than the current operating fleet standard of ∼5% U-235, and perhaps even greater than 20%) and economically uncompetitive in most of today's markets. Moreover, SMRs designed to serve a US base would face the same economic challenges as current commercial reactors, and there is no guarantee that a nuclear design would win the day in a competition for US military base power supply. Even siting, a purported advantage of having the military deploy SMRs, would be difficult. The DoD follows state environmental guidelines when they do not compromise the defense mission. The siting of SMRs would likely still become an issue for the DoD in a range of locations, and not just those that reject nuclear power outright. Finally, having the DoD take the lead in development risks creating several large, expensive, "too-big-to-fail" fiefdoms, which would detract from more pressing warfighting needs (36).

In addition to the practical challenges, there are compelling normative arguments to be made against relying on the DoD to revivify the nuclear enterprise. These revolve around the role of the US military in American economic and civic life.

First, the military develops new technologies when they are the only available solution to a problem. Scenarios proposed for military leadership in SMR design and development do not convincingly make the cut when balanced with alternatives, such as power purchase agreements. Second, we endorse the firebreak between the civilian and military nuclear programs because it has substantial normative value. Third, at a time when American civic and political norms rest on precarious ground, using the military to rescue a commercial industry degrades the social fabric from which it derives legitimacy. It also undercuts the DOE by underscoring its failure to enable the development of advanced reactors.

Most troublingly, adopting this model would amount to an admission of failure on the nuclear industry's part. Defaulting to the national security argument in an effort to salvage the US commercial nuclear industry concedes the failure of the technical and economic arguments in favor of the technology. It also does little to drive commitment from industry that would generate broader deployment. Other options, including long-term power purchase agreements, coordination in human capital development, and research into grid security, constitute avenues for DoD involvement that are more politically credible and economically sound. However, it is unclear that any of these could have more than a modest impact on the development of a domestic SMR industry in the next few decades (36).

Developing a Strategic SMR Export Market. In addition to exploring both prominent and niche domestic markets, we have undertaken an assessment at the national level of the nature and size of the potential global market for light water SMRs.[‡,§] Because energy system

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[†] Rath M, Morgan MG (2018) Assessment of a hybrid system that uses small modular reactors (SMRs) to back up intermittent renewables and desalinate water (Department of Engineering and Public Policy, Carnegie Mellon University).

[‡] Ford M, Abdulla A, Morgan MG (2018) The role of institutional challenges in limiting the global deployment of nuclear power as part of a low-carbon energy strategy (Department of Engineering and Public Policy, Carnegie Mellon University).

[§] Ford M, Abdulla A, Morgan MG (2018) Use of multifactor time series data envelopment analysis (DEA) to assess infrastructure development readiness and risk (Department of Engineering and Public Policy, Carnegie Mellon University).

modelers generally focus on technology deployment rates instead of the ultimate limits to deployment, their work often assumes radical expansion of technologies that are constrained by economic, political, and institutional realities. To assess the impact of these realities on SMR deployment worldwide, we used multiattribute methods and data envelopment analysis, a performance benchmarking technique. Once national institutional quality is considered, we observe a dramatic reduction in readiness for nuclear deployment, including among G20 nations that are large emitters like India, Saudi Arabia, Mexico, Turkey, and Indonesia. A global nuclear enterprise that exports large numbers of SMRs to these nations is likely to be a riskier one, unless substantial investments are made to strengthen oversight institutions in these countries. Given the nationalistic tendencies and ideological retrenchment in these nations (among many others), efforts to assert multilateral oversight over nuclear material and even friendly offers to help enhance national performance are likely to be rebuffed. More importantly, arguments that base the viability of small reactors on their export to nonnuclear nations are inherently weakened by the fact that most (80%) of the decarbonization necessary will have to occur in a handful of nations that are already nuclear-capable. National security considerations make it most unlikely that countries like China, Russia, or the United States would import dozens, let along hundreds or thousands, of SMRs manufactured by a geopolitical rival. Despite our analysis showing that there could be a global market for many hundreds of light water SMRs,[‡,§] we remain skeptical that a US industry of factory-manufactured SMRs could be built primarily on the basis of exports.

Little Chance of a New SMR or Other Nuclear Wedge

From the foregoing, we conclude that in the absence of a dramatic change in market conditions, political will, and substantial subsidies, there is virtually no chance that the United States will be able to undertake the construction of additional large LWR power plants in the next several decades. Indeed, if the United States is going to retain most of its existing fleet of large LWRs, additional programs to subsidize their life extension and continued operation will have to be implemented in just the next few years.

Because the United States will probably not build any new large LWRs, and there is no practical way to bring advanced reactor designs to achieve widespread commercial viability in the United States in less than several decades (23, 24, 37), we have argued that only factory-manufactured SMRs could contribute a significant new nuclear carbon-free wedge on that time scale. For that to happen, several hundred billion dollars of direct and indirect subsidies would be needed to support their development and deployment over the next several decades, since present competitive energy markets will not induce their development and adoption. In addition, the US Nuclear Regulatory Commission would need to find ways to dramatically accelerate its regulatory review processes, including addressing novel design options that depart from current practice, such as systems that encourage automation, multimodule construction and operation, smaller operational and security staffing levels, and perhaps dramatically smaller emergency planning zones. Moreover, a serious national commitment would have to be made to deeply decarbonize the energy system. The signal that this is happening must be strong enough for investors to confidently assume that the direct or indirect cost of emitting carbon dioxide to the atmosphere will lie in the range of \$100 per ton of CO_2 within a decade. All these developments are possible, but we believe they are most unlikely.

The outlook is not quite so grim on time scales of midcentury and beyond. By then, if the world has not reduced greenhouse gas emissions to zero and embarked on a program to achieve negative emissions (4, 5), average global temperature will have risen by well over 2 °C, so a realization of the problem will have become widespread and the need for emission-free energy will be acute. To assure that we have safe and affordable advanced reactor designs that can be deployed at scale by midcentury, the United States will need to dramatically increase and refocus the budget of the DOE's NE toward advanced reactor development. Perceptive and ruthlessly pragmatic program officers will need to be recruited: ones with a sense of the mission's urgency. The government would have to sustain that higher level of support in the face of constant short-term political pressures and, undoubtedly, organized opposition from advocates of other generating sources. Part of that increased budget would have to be dedicated to building new infrastructure, such as fast-flux test facilities and other system test beds. Even with a higher budget, surge funding may be needed in some years to support demonstration reactor development and program leadership would eventually have to focus on moving two or three systematically chosen designs to the point of commercialization. Perhaps these things can happen; the United States is no stranger to ambitious undertakings, but it will take both vision and a level of commitment that are sorely lacking today.

We believe that achieving deep decarbonization of the energy system will require a portfolio of every available technology and strategy we can muster. It should be a source of profound concern for all who care about climate change that, for entirely predictable and resolvable reasons, without immediate and profound changes, we appear to be set to lose one of the most promising candidates for providing a wedge of reliable, low-carbon energy over the next few decades and perhaps even the rest of the century.

Acknowledgments

This work was supported by the Alfred P. Sloan Foundation (Grant 2016-7281); the John D. and Catherine T. MacArthur Foundation (Grant 12-101167-000-INP); the Center for Climate and Energy Decision Making (CEDM) through cooperative agreements SES-0949710 and SES-1463492 between the National Science Foundation and Carnegie Mellon University; the US Department of Veterans Affairs and Carnegie Mellon University Yellow Ribbon Program; the University of California, San Diego Frontiers of Innovation Scholarship Program; and the University of California, San Diego Deep Decarbonization Initiative.

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