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INVITED PAPER

Small Modular and Advanced Nuclear Reactors: A Reality Check

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ABSTRACT Nuclear power has been declining in importance over the last quarter century, with its share of global electrical energy generation decreasing from 17.5 percent in 1996 to around 10 percent in 2019. Small modular and advanced nuclear reactors have been proposed as potential ways of dealing with the problems—specifically economic competitiveness, risk of accidents, link to proliferation and production of waste—confronting nuclear power technology. This perspective article examines whether these new designs can indeed solve these problems, with a particular focus on the economic challenges. It briefly discusses the technical challenges confronting advanced reactor designs and the many decades it might take for these to be commercialized, if ever. The article explains why the higher construction and operational costs per unit of electricity generation capacity will make electricity from small modular reactors more expensive than electricity from large nuclear power plants, which are themselves not competitive in today's electricity markets. Next, it examines the potential savings from learning and modular construction, and explains why the historical record suggests that these savings will be inadequate to compensate for the economic challenges resulting from the lower generation capacity. It then critically examines arguments offered by advocates of these technologies about job creation and other potential uses of energy generated from these plants to justify subsidizing and constructing these kinds of nuclear plants. It concludes with an assessment of the markets for these technologies, suggesting that these are inadequate to justify constructing the necessary manufacturing facilities.

INDEX TERMS Energy resources, fission reactors, nuclear power generation, power system economics, small modular reactors, advanced reactors.

I. INTRODUCTION

Countries around the world have expressed an interest in developing or deploying Small Modular or Advanced Nuclear Reactor designs. The International Atomic Energy Agency records 72 designs in its biennial report on Small Modular Reactors (SMRs) [1]. While there have been earlier efforts to develop and market SMRs, these have not been successful [2]–[4]. Promoters of SMRs make promises about how these reactors are the future for nuclear power, solving many of the problems that have held back the technology [5]–[9]. They also assert that SMRs are uniquely suitable to evolving energy markets, because of technical characteristics like load following capabilities and their ability to produce high-temperature heat.

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This perspective article evaluates some of these claims, in the backdrop of an important constraint: economic competitiveness. It starts with a brief overview of the historical evolution of nuclear power and the drivers for SMR development. This is followed with discussions of the economic challenges that confront SMRs, the designs that are more likely to be built in the near to medium-term future. It then examines a few of the other arguments made by advocates of these technologies to obtain government support. It concludes with some prognostic comments about markets for these reactor designs.

II. HISTORICAL AND ECONOMIC SCENARIO

Underlying the drive for SMRs and advanced nuclear reactors is the decline in nuclear power over the last quarter century, coming down from providing 17.5 percent of the global electrical energy generated in 1996 to around 10 percent in 2019 [10], [11]. The main problem has been economics.

As the 2003 Massachusetts Institute of Technology study put it baldly, "Today, nuclear power is not an economically competitive choice" [12, p. 3]. The same study also identified the risk of accidents, the production of radioactive waste, and the link to nuclear weapons production as problems.

This economic evaluation was made just as the global nuclear energy market was said to be on the verge of what was termed a nuclear renaissance [13]–[17], propelled in the United States by the Energy Policy Act of 2005 that offered various guarantees and incentives to nuclear power [18].

That hoped-for renaissance fizzled out in a few years and by 2012, John Rowe, former chairman and CEO of Exelon Corporation, then the largest nuclear operator in the United States, candidly admitted: "Let me state unequivocably that I've never met a nuclear plant I didn't like…Having said that, let me also state unequivocably that new ones don't make any sense right now" [19]. The new ones that Rowe was talking about were the Advanced Passive 1000 (AP1000) reactor designs being built in the states of Georgia and South Carolina in the United States.

Both of these vastly exceeded the initial cost estimates, with the Vogtle project currently forecast to cost $29 billion compared to $14 billion when construction started [20], [21]. When construction started, the utility in charge projected that the first of the two reactors being built would "come online in 2016 and the second one in 2017" [20]. As of February 2021, neither reactor has started operating.

The other nuclear project in South Carolina was abandoned in 2017 after $9 billion were spent on it [22]. The failure caused Westinghouse, the company directly or indirectly responsible for the design of the majority of the world's nuclear reactors, to file for bankruptcy protection [23], [24].

This pattern of cost and time overruns was observed in other countries as well. In France, the Flamanville 3 project is "running a decade behind schedule" and "expected to cost 12.4 billion euros" [25] much higher than the 3.3 billion euros forecast when construction started [26, p. 39]. The construction cost of Russia's Leningrad NPP-2 power plant went up from an estimated 133 billion rubles to 244 billion rubles (about 8 billion USD) [27, p. 171]. India's Koodankulam reactors were estimated in 2010 to cost Rs. 131.71 billion [28], but this went up to Rs. 224.62 billion ($3.5 billion) [29].

Some countries, most prominently China, have continued to build nuclear plants. But construction in all countries has slowed down substantially in comparison with earlier plans and global projections for nuclear power capacity have decreased. The ongoing nuclear construction should be viewed as part of these countries adopting a strategy that involves building out many different sources of power rather than a focus on nuclear power, and in the context of much larger installations of solar and wind energy [10].

It is in this context that one should view the argument that if nuclear power needs to grow, it could only be on the basis of a new generation or novel kinds of nuclear reactors. Small modular reactors or advanced reactors are part of such hoped-for solutions.

III. SMALL MODULAR AND ADVANCED NUCLEAR REACTORS

We start with a few clarifications about nomenclature. The terms "small", "modular", and "advanced" reactors do not refer to any specific design or designs and there is considerable overlap between different categories. Note that almost all of these are only conceptual designs and not operational or fully complete designs. While SMR designs should possess the two characteristics that are explicitly included in their name, namely "small" and "modular" (defined later), the category of advanced nuclear reactors is quite vague and in principle any reactor design today can claim to be advanced. Indeed, many of the nuclear reactors constructed in the world today have been a result of programs from the 1980s and 1990s to develop "advanced" designs, including advanced light water reactors [30]–[33]. Further, many reactor designs can be considered an advanced reactor or an SMR or both. For example, the Xe-100 high temperature reactor is listed as an SMR by the International Atomic Energy Agency [1], but received $80 million in 2020 from the U.S. Department of Energy's Advanced Reactor Demonstration program.

During the early 2000s, there was an organized international research effort to develop what were called Generation IV nuclear energy systems, that were to provide significant improvements in economics, safety, sustainability, and proliferation resistance [34]. Generation IV reactors can be small or large. Regardless of size, various characteristics of Generaion IV reactors do apply to many SMR and advanced nuclear reactor designs.

The most pertinent of these characteristics for our discussion is their technological readiness, or lack thereof. When this initiative was established in 2000 "with the aim of fostering the research and development necessary to underpin the development of a new generation of nuclear energy systems", the goal was "commercial deployment by 2020–2030" [35, p. 4323]. That deadline has slipped, and the 2018 update from the Generation IV forum concluded that "readiness for commercial fleet deployment" has been pushed back to "around 2045 (for the first systems)" [36].

This lengthening deadline is because these so-called advanced reactor designs are incomplete, with major technological challenges that need to be overcome before they can be considered ready for deployment. In 2015, the French Institut de Radioprotection et de Sûreté Nucléaire (IRSN) examined these reactor designs and concluded 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" [37].

Note that the timeline of "first half of the 21st century" is well beyond the kinds of timelines required for meeting the more ambitious climate mitigation challenges laid out by the Intergovernmental Panel on Climate Change and other international and national agencies. Experience has shown that SFRs, the one Generation IV design held out by IRSN as relatively mature, are expensive, prone to accidents, and to operational problems [38].

Now we turn to SMRs. As their name suggests, these are designed to produce relatively small amounts of power compared to the current nuclear reactor fleet, with small being defined as less than 300 megawatts (MW) of electricity. The term modular is used to refer, in part, to the idea that one nuclear reactor with a large power output is replaced with many reactors with smaller power output. The other sense in which the term modular is used is to emphasize that, instead of trying to build the whole nuclear plant on the site from scratch, the reactor is assembled on site from various modules that have been manufactured in factories.

The terms "small" and "modular" are just two characteristics of the design and there are a range of fuels, moderators, and coolants that could be used in different kinds of SMRs [1], [39]. Depending on design choices, the physical size of these plants can be small or large, with little connection to the generation capacity.

IV. ECONOMIC CONSEQUENCES OF REDUCED OUTPUT

Small reactors, modular or not, are expected be more expensive per unit of output because of something that economists have known for decades and termed economies of scale [40]–[42]. Larger reactors (or other power plants for that matter) are cheaper on a per megawatt basis because their capital and operating costs, which represent material and work requirements, do not scale linearly with generation capacity. This is reflected in a general rule of thumb followed in industrial engineering which uses a power law to relate the capital costs of production facilities with different capacities, with an exponent that is usually chosen to be 0.6 [43, p. 421]. Other studies use different numbers for the exponent (e.g. 0.55 used in a study by the Canadian Nuclear Laboratories [44]) but none of them expect that the exponent will be one. With an exponent of 0.6, if there are two plants of size S_1 and S_2, the ratio of their capital costs K_1 and K_2 is given by:

$$^{K_1}/_{K_2} = \left(^{S_1}/_{S_2}\right)^{0.6}.$$

This formula implies that, all else being equal, a SMR with a power capacity of 200 MW would have a construction cost of around 40 percent of the cost of constructing a 1000 MW reactor, whereas it would generate only 20 percent of the electricity. Thus, the 200 MW SMR has roughly twice the cost per MW of capacity. Similarly, operating an SMR will also be more expensive per MW of capacity in comparison with a large reactor due to diseconomies of scale. Both of these factors will result in a higher cost per unit of electricity generated.

Small modular and advanced nuclear reactor designers often argue against the application of such scaling laws because, according to them, their designs are so different from current reactors as to invalidate scaling. While that might have some truth, and these power laws cannot be taken as exact ways to calculate costs, the general principle about economic losses due to smaller size will still hold.

Further, there are two corollaries that flow from this argument about differences in designs. First, the lack of experience with these designs means that estimates of cost and construction time are much more uncertain, and will likely suffer from the huge overruns that have been typical of "First of a Kind" projects [45]–[47]. Second, new designs will mean that the process of getting safety approvals ought to be more demanding, at least in any well-designed and well-functioning regulatory system, and thus more expensive. To give a sense of scale of expenditures involved, the development of the NuScale SMR design had cost $957 million till March 2020, of which the U.S. government has contributed $314 million [48]. It is expected that another $500 to $700 million will have to be spent before the design receives the regulatory approval for construction to commence [49], [50]. This total research and development cost of roughly $1.5 billion is for a scaled down, light water reactor design, the most prevalent nuclear reactor design in the world.

Completely new designs envisioned by Advanced nuclear reactor and some SMR developers should cost even more to translate from conceptual design to one that is licensed to be constructed. There is simply no appetite within the private sector to underwrite such large risky investments. A good illustration is Bill Gates who has spent billions on various philanthropic efforts but still seeks government subsidies for his nuclear venture [51]–[53].

V. CAN LEARNING COMPENSATE?

Proponents of small modular reactors argue that they can make up for the lost economies of scale by savings through mass and modularized manufacture in factories and resultant learning [54]–[60]. Learning in this context refers primarily to the reduction of cost with increased construction. It is often quantified through a learning rate, which is defined as the percentage cost reduction associated with a doubling of units produced [61].

The economic case for SMRs critically rests on fast learning. What do we know about learning? Early in this century, a study from the University of Chicago concluded that "a reasonable range for future learning rates in the United States nuclear industry is 3 to 10 percent" [61, pp. 4–24]. Even the upper estimate is low compared to most other energy technologies [62]–[64].

Further, for such rates of learning as expected for the nuclear industry, the same SMR design will have to be manufactured by the thousands, for the cost of electricity from SMRs to break even with the corresponding cost of electricity from large reactors [39]. There is unlikely to be a market for so many highly priced SMRs; these units will not even competitive with large nuclear power plants, let alone other sources of electricity. Expert assessments of projected costs of SMRs bear out the prognosis that learning will not adequately compensate for diseconomies of scale [72], [73].

Sustained learning would also require just one or two standard reactor designs to be chosen for build-out in those large quantities. However, as mentioned earlier, roughly six dozen SMR designs are in various stages of development in multiple countries [1]. It is very unlikely that one, or even a few designs, will be chosen in a coordinated fashion by different countries and private entities, discarding the vast majority of designs that are currently being invested in.

In the case of large nuclear reactors, there are many, very different, designs being constructed even now, after decades of construction experience. SMRs and advanced reactors under development currently have very different designs and seek to exploit different niches. Such differences do not help with standardization.

The prognosis for cost reductions is even worse. When we look at the historical record, the evidence suggests that at the fleet level nuclear power could even have what has been termed a negative rate of learning. In the United States and France, the two countries with the largest nuclear reactor fleets, reactors that were constructed later actually cost more than those constructed earlier [65]–[71]. If this pattern holds for SMRs, it would mean that a small reactor will never catch up on cost with a large reactor of similar design.

VI. CAN MODULAR CONSTRUCTION HELP?

As mentioned earlier, SMR promoters emphasize the importance of ''modular construction'', wherein many components of the reactor are manufactured in factories and put together on the site, to reduce cost. This has become standard practice in much of today's manufacture, for example, in house construction. The practice has also been incorporated into nuclear reactor manufacture for a while, especially by Westinghouse.

Westinghouse has emphasized this practice in the design of the AP1000 reactor and that of the proposed, but never built, pebble bed modular reactor in South Africa [74, p. 1860], [75]. But the experience of the AP1000 reactors built in the United States and China shows that this strategy is also problematic, albeit in a different way from conventional manufacture. Most importantly, nuclear reactors built in a modular fashion are not spared the curse of high capital costs. As a former member of the Georgia Public Service Commission, the state utility authority overseeing the Vogtle nuclear power plant in the United States, told the *Wall Street Journal*, ''Modular construction has not worked out to be the solution that the utilities promised'' [76].

A specific example of how modular construction has not helped concerns one of the important parameters that determines the economics of a nuclear project: the time to construct a nuclear plant. Building a large nuclear plant, from the first pour of concrete to being able to power homes and offices, takes about ten years [10]. As against this historical reality, modular construction was expected by its proponents to reduce the time frame dramatically. In 2014, for example, a senior Westinghouse official claimed that the ''AP1000 design saves money and time with an accelerated construction time period of approximately 36 months, from the pouring of first concrete to the loading of fuel'' [77]. In contrast, the Haiyang project in China took around 9 years to go from construction start to being declared commercial [78]. Construction costs, too, grew dramatically. The AP1000 reactors under construction in the United States have fared even worse.

The AP1000 is by no means a one-off case. There is a long history of underestimating the time it would take to complete a nuclear power plant around the world. Indeed one study of construction cost overruns showed that 175 out of the 180 nuclear projects examined had final costs that exceeded the initial budget, on average by 117 percent; they took on average 64% more time than projected [47], [79]. What is special about the AP1000 is that it was supposed to be an exception to this pattern because of ''modular construction'' – and it ended up becoming one more instance of this pattern.

Small modular reactors, too, have suffered cost and time overruns. For example, Russia's KLT-40S that is intended for deployment on a barge as a floating nuclear power plant, has taken about four times as long as originally projected. Initial projections in 2006 foresaw the plant being constructed in about three years, but it took over 12 years for the plant to be connected to the grid [10]. Cost estimates have quadrupled. There have been no further orders for the KLT-40S.

When confronted with the economic challenges associated with SMRs and advanced nuclear reactors, advocates of these technologies resort to a number of other arguments to persuade policy makers to offer support. In what follows, we examine a few of these.

VII. WILL SMALL MODULAR AND ADVANCED NUCLEAR REACTORS BE MAJOR JOB CREATORS??

One reason frequently offered for why governments should support SMR development is that investing in SMRs will lead to job creation [80]–[83]. Of course, investment in SMRs will lead to jobs. That is but a trivial observation. The real question is whether the number of jobs created by investing a certain amount of money in SMRs exceeds the number of jobs created by investing the same amount of money in a different but comparable energy technology.

Although there is no data on jobs from SMRs—because SMRs have not been deployed at any meaningful level to measure employment figures—the literature is clear that nuclear power generates fewer jobs than renewables like solar and wind energy per unit of energy generated [84], [85]. To the extent that one can make prognoses about the number of jobs that might be created by advanced and small modular nuclear reactors, the outlook would be even more bleak. Most of these designs are aimed at reducing the numbers of operators, because the main challenge faced by nuclear power is cost. There are even those who envision nuclear reactors operating in a completely automated fashion (for example [86]), or with minimal operators (e.g., [87]). Thus, one would expect SMRs and advanced to generate fewer jobs per unit of electricity output (in megawatt-hours) in comparison to other energy technologies.

Conversely, because nuclear jobs are high paying, operating costs of nuclear power plants will be very high. For example, the nuclear reactor developer Oklo in the United States has stated that it anticipates ''15 full time and well-paying jobs'' that are ''available to local residents with a high school education'' for its 1.5 MW plant [88]. The document does not define what well-paying means. According to the U.S. Bureau of Labor Statistics, the annual pay for US nuclear power plant operators, distributors, and dispatchers in 2019 was $85,950 [89]. (Note that this is the wage for someone with a high school diploma or equivalent qualification at the time of entry, not for a highly educated nuclear engineer, who can earn over $120,000.) Putting these together, just the operational cost of electricity from an Oklo reactor will be $109 per megawatt hour if the reactor were to operate at a 90 percent capacity factor, which is an optimistic assumption for a remote site where the nuclear plant will have to vary its output according the changes in demand or load. In other words, even if the capital cost of the reactor and fueling cost are zero, the cost of electricity from a hypothetical Oklo power plant will be nearly three times that of new solar or wind power plants [90]. Note that this is just the generation cost at the busbar and the costs for transmission and distribution have to also be incorporated to compare with residential costs.

Since the cost of solar and wind power are declining, the difference will be even greater by the time the Oklo reactor moves from theoretical proposal to a licensed and constructible design. This large difference in costs implies that SMRs would be likely be much more expensive even after accounting for the system costs of other ways of managing the variability of solar and wind power, such as adding storage. The dismal economics of Oklo mean that if any are actually built, it will be because of large government subsidies. Given this dependence on government funding, one can expect that even in the best case, only a few such reactors will be constructed, which then means that the number of jobs generated will be miniscule.

VIII. CAN SMRS SUPPORT ELECTRICAL GRIDS WITH LARGE FRACTIONS OF RENEWABLES BY LOAD FOLLOWING?

The capability to adjust a plant's power production to respond to variations in electricity demand is termed load following. Several advocates have argued that SMRs are capable of load following [56], [91]–[94]. Some of these authors refer to the ability to change output over relatively long periods of time, for example, between night and day. However, with the increased share of variable (what is sometimes termed intermittent) electricity sources such as wind or photovoltaic power, some nuclear designers have emphasized the capability of SMRs to quickly change their output in response to changes in the outputs of wind or solar plants (for example [94]). Load following capabilities would be essential to the deployment of SMR designs ''off the grid'' in remote areas.

Although nuclear power plants are capable of load-following operations, and this has been done in some countries, particularly in France and Germany, nuclear reactors do have technical limitations that constrain their capability to operate in a load-following mode [95], [96]. From a technical point of view, shutting down, restarting, or varying the output power are all more challenging for nuclear power plants, especially water-cooled reactors, compared to other electricity sources. Frequent and steep temperature changes accelerate interactions between the nuclear fuel and the metallic cladding, which, with time, might lead to rupture of the cladding and the escape of fission products. Such changes can reduce operating life and increase maintenance costs.

Because of such safety concerns, regulators require the power variation rate to be confined within specific margins. In currently deployed nuclear technologies, the range of allowed power variation rates is between 1–5 percent of the rated power per minute. The European Utilities Requirements (EUR) document requires the capability to operate between 50 and 100 percent of the plant's rated power over a day, with a rate of change of electrical output of 3 to 5 percent of the rated power per minute [95]. This limited ability to change outputs from nuclear reactors might not be fast enough to compensate for the potentially rapid changes of outputs from wind and solar power plants.

Further, although load following may be technically possible, operating reactors in this mode would decrease their economic competitiveness. The challenge arises from the fact that nuclear power plants have high fixed (capital) costs. Therefore, it makes more economic sense to operate them continuously near their maximum capacity in order to improve the return on investment. On the other hand, oil-fired or gas-fired peaking plants are better used to cover peak electricity demand because of their low capital and high fuel costs. Operating nuclear reactors in a load-following mode would reduce the capacity factor, which would increase the cost of electricity generated in these.

When deployed on a grid in conjunction with a large share of renewable energy sources, nuclear plants will not operate with the typical 90 to 95 percent capacity factors that are typically assumed in economic analyses of these power sources. Should the capacity factor decrease, the cost of generation will increase because the capital and operating costs will have to spread out over fewer kilowatt-hours. In the case of the NuScale SMR, the cost of generating electricity goes up by about 20 percent if the capacity factor is reduced from 95 percent to 75 percent [50]. Given the already poor economic prospects for SMRs, this penalty will essentially rule out deployment of these technologies in a load-following mode.

Small modular reactor advocates propose that the energy not utilized to produce electricity is used for other purposes, such as desalination [97]–[99], or co-generating hydrogen [91], [100]. Such strategies are also proposed by advocates for renewable energy sources [101]–[107]. For most SMRs, hydrogen is produced by using electricity to electrolyze water, the same as when using renewables. The key difference is that the costs of nuclear energy, especially from SMRs, are prohibitively high and rising, whereas the costs of renewables are low and declining. More narrowly, renewables benefit from the almost zero marginal costs of solar and wind energy because they don't incur any fueling costs and operator costs are minimal. A few SMR and advanced reactor designs that do not use water for cooling might be able to utilize high-temperature electrolysis at higher efficiencies. However, as discussed earlier, these designs are far from ready and it is not possible to carry out any meaningful economic analyses of these at present.

IX. DO SMRS LOWER THE LIKELIHOOD OF SEVERE ACCIDENTS OR PRODUCE LESSER AMOUNTS OF RADIOACTIVE WASTE OR LOWER THE RISK OF PROLIFERATION?

Proponents claim that SMRs and advanced reactors have improved safety, reduce radioactive waste generation, and increase proliferation-resistance. Before we address the veracity of this claim, it should be remembered that SMRs and advanced nuclear reactors also suffer these problems, albeit to different extents from standard large light water reactors. Thus, building SMRs or advanced reactors will also expose citizens to these risks.

Because SMRs and advanced reactors encompass a large number of disparate designs, it is not possible to make generalized statements. For example, SMRs based on fast reactor technologies will produce a lower quantity of nuclear waste per unit of electricity generated, whereas SMRs based on light water reactor technologies will produce more waste per unit of electricity generated; but both pose higher risks of proliferation as compared to large light water reactors [117]. (The difference between SMRs based on fast reactor technologies and those based on LWRs is the burnup; the former typically envision in-situ breed-and-burn to maximize fuel burnup whereas the latter typically adopt a simplified all-in/all-out core management scheme that lowers the burnup; in both cases, the smaller size of the reactors contributes to lowering the burnup because more neutrons will escape the core in comparison to larger reactors).

The volume of waste is not always the most relevant variable; the size of the geological repository needed for waste burial is dependent on heat production and waste composition [118]. Wastes from fast reactors and other forms of SMRs not based on light water reactor technology can be corrosive and/or pyrophoric and dealing with these forms is more complicated and the necessary processing before disposal might actually end up increasing the volume [119]. Many SMR and advanced nuclear reactor designs are fueled by plutonium, which necessitates the processing of spent fuel, often at a reprocessing plant; reprocessing plants could produce increased quantities of different kinds of radioactive wastes [120], [121].

When it comes to the risks of accidents, all else being equal, a smaller reactor could be safer because of the smaller inventory of radioactive material and lower amount of energy available for release during an accident. However, all else is seldom equal. Small modular reactor proposals often involve building multiple reactors at a site to try to lower costs by taking advantage of common infrastructure elements. NuScale, for example, proposes to build twelve reactor modules at each site. Multiple reactors at a site increase the risk that an accident at one unit might either induce accidents at other reactors or make it harder to take preventive actions at others. It is also possible to have multiple units simultaneously undergoing accidents if the underlying reason for the accident is a common one that affects all of the reactors, such as an earthquake. With multiple reactors, the combined radioactive inventories might be comparable to that of a large reactor.

More generally, the technical characteristics of SMRs do not allow them to simultaneously solve all these problems [122]. When examined in detail, SMR and advanced nuclear reactor designs that are being developed turn out to make choices about which problem to focus on and make trade-offs between desired features. Designs that optimize one metric, say waste volume, might make other challenges, such as the risk of severe accidents, more acute.

X. IS THERE A MARKET FOR SMRs?

The evidence so far suggests that there is little demand for SMRs. SMRs developed in Russia (KLT-40S), China (HTR-PM), and South Korea (SMART) have not found customers [10]. In the United States, the first proposed SMR project involving the construction of a NuScale reactor design has run into trouble, with many utilities that had signed up for the project choosing to exit the process as the high cost became more evident [108]–[110].

Although many developing countries claim to be interested in SMRs, few seem to be willing to invest in the construction of one. Good examples are the cases of Jordan, Ghana and Indonesia, all of which have been touted as promising markets for SMRs, but none of which are buying one [111]–[113].

Niche markets, for example, remote mines and communities that are not otherwise served by the grid and that are currently electrified using diesel plants with very high fuel costs, are quite limited. Indeed, even in a best case scenario, where economics plays no part and where nearly every potential user of SMRs purchases a small modular reactor, the net demand from remote mines and communities in Canada was shown to be far smaller than the minimum demand necessary to construct the factories needed to build these reactors [114]. Further, such remote sites have often provided attractive renewable opportunities [123]–[125].

The lack of adequate demand, either in niche markets, grid connected markets, or developing countries, is a major constraint because of the emphasis on modular construction by SMR and advanced nuclear reactor designers. As one SMR designer admitted, "A supplier would have to foresee a sufficient market to invest in factories large enough to achieve economy of mass production from production runs of many hundreds of turnkey plants" [115, p. 688].

If there is no market to set up a factory, then SMR plans run into a chicken and egg problem: without the factory, they cannot ever hope to achieve the theoretical cost reductions that are at heart of the strategy to compensate for the lack of economies of scale.

XI. CONCLUSION

Expectations that small modular or advanced nuclear reactors will rescue nuclear power are unlikely to be met. Most advanced nuclear reactor designs are simply not ready for deployment or commercialization because of technical problems. Small modular reactors, for their part, start off being less economical than large reactors because of their smaller power outputs without correspondingly smaller costs. Various methods of modifying SMRs and advanced nuclear reactors to load-follow or co-generate hydrogen or desalinate water do not help. Nuclear advocates seem to be clutching at straws by emphasizing these options.

Pursuing SMRs will only worsen the problem of poor economics that has plagued nuclear power and make it harder for nuclear power to compete with renewable sources of electricity. The scenario is even more bleak as we look to the future because other sources of electricity supply, in particular combinations of renewables and storage technologies such as batteries, are fast becoming cheaper.

Finally, because there is no evidence of adequate demand, it is financially not viable to set up the manufacturing facilities needed to mass produce SMRs and advanced reactors. All of these problems might just end up reinforcing *The Economist* magazine's observation from the turn of the century: "nuclear power, which early advocates thought would be 'too cheap to meter', is more likely to be remembered as too costly to matter" [116].

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