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One size doesn't fit all: Social priorities and technical conflicts for small modular reactors

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ABSTRACT

Small modular reactors (SMRs) have been proposed as a possible way to address the social problems confronting nuclear power, including poor economics, the possibility of catastrophic accidents, radioactive waste production, and linkage to nuclear weapon proliferation. Several SMR designs, with diverse technical characteristics, are being developed around the world and are promoted as addressing one or more of these problems. This paper examines the basic features of different kinds of SMRs and shows why the technical characteristics of SMRs do not allow them to solve simultaneously all four of the problems identified with nuclear power today. It shows that the leading SMR designs under development involve choices and trade-offs between desired features. Focusing on a single challenge, for example cost reduction, might make other challenges more acute. The paper then briefly discusses other cultural and political factors that contribute to the widespread enthusiasm for these reactors, despite technical and historical reasons to doubt that the promises offered by SMR technology advocates will be actually realized.

1. Introduction

Nuclear power advocates have been looking to revive a high-rate of construction of reactors and to retain, if not increase, electricity market share worldwide in the face of the well-known problems associated with this technology. In 2003, a Massachusetts Institute of Technology study on the future of nuclear power traced the "limited prospects for nuclear power today" to "four unresolved problems": Costs, Safety, Waste, and Proliferation [1]. All these have become more salient in the past decade due to various causes such as the economic downturn, the Fukushima nuclear accidents, the continuing failure to site and operate a permanent repository for spent nuclear fuel and other radioactive wastes, and the rapid decline in renewable energy costs.

Inasmuch as they reflect the priorities and desires of various sections of society, these problems are ultimately social in origin and the recognition by nuclear reactor vendors that these are problems to be dealt with is a reflection of popular struggles. The social science literature on many of these problems, as well as other topics related to nuclear power, is vast, and has included detailed examinations of subjects as varied as, but not limited to, dealing with long-lived nuclear waste [2–5], trust in nuclear institutions [6–9], risk perception [10–15], the problematic nature of the production of "expert knowledge" about reactor accidents [16,17], anti-nuclear movements [18–20], national nuclear policy making [21–28], nuclear power in the sociotechnical imaginaries of different countries [29], choices of reactor technologies and fuel cycles [30–32], economics of electricity generation [33–37], and technological learning [38–41].

This paper offers such an examination of the development of new reactor designs over the last few years. During this period, much hope has been invested in what are called Small Modular Reactors (SMRs) as a possible way to address all four of the above-mentioned key problems with existing nuclear reactor designs and fuel cycles and thereby offer a brighter future for nuclear power. SMR designs typically have power levels between 10 and 300 MWe, much smaller than the 1000–1600 MWe reactor designs that have become standard [42–44]. Several countries are in the fray to develop SMRs, including the United States, Russia, China, France, Japan, South Korea, India, and Argentina. Several of these countries are providing substantial government support for such reactors.[1]

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[1] It is likely that government funding both reflects the interests of the nuclear industry and drives such interest.

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Regulatory agencies in these countries are also in the process of grappling with licensing SMRs, many of which incorporate novel features in their designs [46].

Proponents of SMRs have made extensive claims, directed both at large industrialized countries and developing countries, about the purported benefits of SMRs and their abilities to help meet various social and environmental goals.[2] These claims are echoed by government departments such as the U.S. Department of Energy and international bodies charged with promoting nuclear power such as the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency (NEA). Many of these actors have also fostered an expectation that the SMR market will be large [48–50].[3]

This paper starts with an overview of the claims made by SMR proponents aimed at persuading policy makers and the public about the virtues of the technology, and how these relate to the social priorities listed earlier. We then examine the technical characteristics of SMRs and show that, rather than capturing all four of these desirable features, the leading SMR designs under development involve choices and trade-offs between desired features. This implies that SMRs are unlikely to solve all the challenges confronting nuclear power, and indeed, by focusing on some aspects, might make other challenges more acute. The paper then concludes with a brief discussion of the other cultural and political factors that contribute to the widespread enthusiasm for these reactors, despite technical and historical reasons to doubt that the promises offered will be actually realized.

2. The promises of SMRs

The motivations offered for SMRs are all, directly or indirectly, related to the four unresolved problems mentioned by the MIT study, and can be divided into two categories. The first set of motivations are related to the economics of nuclear power, seen by many as the greatest challenge confronting wider deployment of reactors. The second set is focused on ameliorating the other three problems: enhanced safety, reduced nuclear waste production and increased proliferation resistance.

2.1. Economics

The first key problem of current nuclear power technology that SMRs are supposed to resolve is that of cost. The problem has become especially salient as increasing costs of nuclear reactor construction have raised investment risks, and uncertainties have grown about the future size and regulatory structure of electricity markets. Both the risk and uncertainty have been heightened by the global economic crisis experienced by most national economies and industries since 2008, which has served to limit access to capital and increased the search for profit-taking from existing investments and supply chains.

A primary motivation for the nuclear industry to switch to a new kind of a reactor is the high upfront capital cost of standard reactors, which is beyond the financing capacities of many utilities and countries.[4] In the United States, for example, a typical utility that is already invested in nuclear power has a total asset value of about $40 billion, a market capitalization of about $17 billion, and annual revenue of about $13 billion [54].[5] The initial estimated cost of the twin 1 GW reactors proposed for Vogtle, Georgia in the United States was $14 billion [55]. Thus, investing in a nuclear reactor of that capacity represents a significant financial risk for the utility.[6] In comparison, vendors of SMRs project total capital costs of the order of hundreds of millions of dollars to two billion dollars [43]. If these cost estimates were to hold true, it would reduce the overall capital at risk.

Another economic reason that tilts in favor of SMRs as compared to large nuclear reactors is that in many industrialized countries, the rate of growth of electricity demand has dropped to very low levels making large one-time additions of generating capacity difficult to justify in the short to medium term. Building SMRs in multi-reactor clusters “could efficiently match incremental capacity addition with incremental demand growth” [56]. Constructing reactor capacity in smaller increments is also said to have the advantage of operational flexibility [42]. Vendors claim that such incremental reactor construction minimizes financial risk [57].

Justifying large generating units has become even more difficult with the ongoing electricity sector restructuring process around the world, leading to a greater emphasis on economic competition. The OECD’s Nuclear Energy Agency points out that, because of the risks faced in competitive electricity markets, “investors tend to favor less capital intensive and more flexible technologies” [58]. In cases where there is uncertainty in electricity prices, “modular investment. . . [makes] it possible to adapt to the uncertain market conditions, and. . . may be preferred to an irreversible large power plant investment, even if its production costs are higher” and “in an uncertain environment, the choice with the lowest production costs is not necessarily the choice that maximizes the investor’s expected profit” [35].

SMRs are also said to lower the economic risk involved in nuclear generation by reducing the construction time. Reactor construction times are a critical determinant of the economics of nuclear power [59]. SMR advocates compare the total construction time for a LWR, assumed as five years, with a generic SMR construction time of three years to argue that the time to market difference promotes the choice of an SMR [60]. Some reactor vendors and designers claim even shorter construction periods. The Chinese ACP-100 is projected to have a 30-month construction period [61], while Westinghouse has projected an 18-month construction time for its SMR [62].

The problems of private nuclear power investment in developed economies have driven a search for new markets for nuclear reactors. SMRs advocates highlight the opportunity provided in principle by this technology to bring nuclear power to countries with relatively small electrical-grid capacities. A key technical requirement for implementing nuclear power is a reliable grid that

[2] Our brief analysis of these efforts at communicating to and persuading the general public and policy makers speaks to some of the research questions identified in the inaugural issue of this journal, for example, the “types of information” that “are most effective at influencing energy producers” to adopt SMRs and the formation of fantasies [47].

[3] For example, in April 2012, Kate Jackson, a Westinghouse senior vice president and chief technology officer, reportedly stated about the Westinghouse SMR design: “This (small) plant will appeal to a very broad market” [51]. Or, as John Kelly of the U.S. Department of Energy stated to the Nuclear Regulatory Commission on March 29, 2011, “I think it’s very important to point out in the beginning, we’re not talking about deploying a few, or even a handful, of SMRs; we need to be thinking of a fleet: hundreds or thousands of small modular reactors” [52]. There are also claims about specific niches that might provide substantial market opportunities, for example replacing coal power plants that are to be shut down in the United States alone is projected to be worth over $30 billion [53].

[4] See for example the testimony of Christopher Mowry, former President of Babcock & Wilcox Nuclear Energy, before the Committee on Science and Technology, U.S. House of Representatives, 19 May 2010.

[5] There is, of course, a range for these values. In 2011, Entergy, the utility that is highest on the Fortune 500 ratings, had an asset value of $52.2 billion, a market capitalization of $26.8 billion, and revenues of $18.5 billion.

[6] This is not a major problem for countries like France where the government owns the majority share in the electricity generation sector. The role of private companies in the United States may explain the lower levels of interest in SMRs in Europe as compared to the United States.

is large enough to accommodate a standard reactor [63]. In order that the electricity grid remain stable even if one power plant is shut down for some reason, it is recommended that no single power plant provide more than 10% of the regional grid capacity. Thus, if one were considering the kinds of nuclear power plants that are currently being constructed with a typical generation capacity of about 1 GW, then a minimal requirement is that the grid to which it is connected has a capacity of 10 GW or more.

In a survey of 52 countries that, according to the IAEA, were interested in building their first nuclear power plant as of 2009, at least 16 countries did not fit the 10 GW grid capacity requirement [64]. These countries, therefore, should in theory prefer an SMR as compared to a large LWR. A further ten countries also had small overall capacities, but are well-connected with electricity grids in neighboring countries, which permits them to, at least technically, exchange electricity with them and hence could support a larger reactor. However, if such interconnections do not turn out to be feasible for one reason or the other, they too should prefer an SMR.

If financing for a large reactor is a problem with developed countries, it is even more of a problem in many of the smaller developing countries. However, many developing countries have state owned electricity supply companies. Hence a more appropriate financial indicator of the ability to purchase nuclear reactors is a metric like the gross domestic product (GDP). Of the 52 countries mentioned earlier, at least a quarter of them did not possess the financial criteria deemed necessary—an annual GDP of $50 billion (2000 dollars) or more and an annual GDP per capita of $1000 (2000 dollars, using purchasing power parity conversion factors)—to construct a large nuclear power plant [64]. Again, some of these countries will be able to afford an SMR.

Some proponents of SMRs have also argued that standard reactors require the capacity to fabricate and transport large pieces of equipment such as pressure vessels; these can be transported only to coastal regions or along major rivers. Thus the utilization of large pieces of equipment serves to restrict the geographical locations where such reactors can be sited [60]. Further, even if more favorable sites are chosen, many of these countries may also not have adequate local infrastructure to support the construction of a nuclear reactor; it has been argued that SMRs, because they are smaller, can be transported more easily in a (nearly) fully completed state.[7]

Centralized reactor component construction and assembly in the vendor's supplier state also enable the supplier to potentially retain more of the potential profit from a reactor supply contract, rather than have to pass it down the supply chain to third-country or host nation sub-contractors closer to the intended reactor installation site.

The following lines from the brochure of the 2nd Annual Small Modular Conference held in South Carolina, USA in 2012 sums up many of these arguments:

> "nuclear construction projects present huge billion dollar challenges that many utilities and national energy authorities simply cannot risk... Small Modular Reactors are the perfect solution to this problem by mitigating $billions in financial risk, growing incrementally with power demand and offering shorter and easier construction schedules... The SMR market is global and extremely vast with over 80% of countries unable to host large units, military, heavy industry and desalination facilities needing cost efficient power production as well as oil dependent municipalities being crippled by rising fossil prices. In short the power industry is crying out for commercial SMR projects throughout the world".

2.2. Safety, waste generation and non-proliferation

Proponents of SMRs also claim advantages with regard to the other problems identified by the MIT study to motivate those reactors. Perhaps the most important of these, especially in the aftermath of Fukushima, is safety. Concern about catastrophic accidents has been a key factor both in increasing costs and lowering public and government support for nuclear power. Nuclear power construction peaked in 1984 and 1985, reaching 33 grid connections in each year, only to be interrupted by the Chernobyl accident; in 1990 for the first time the number of reactor shutdowns outweighed the number of startups [66]. Several governments decided to phase out nuclear power or abandon plans for the construction of their first nuclear reactor in the aftermath of the multiple reactor meltdowns at Fukushima [67]. So it is but natural that advocates highlight any putative safety advantages of SMRs. This line of argument has been adopted even by independent analysts; one of them dubbed SMRs a "promising direction for nuclear development" in part because they "cap safety hazards" [68].

Proponents suggest that SMRs offer "increased safety by eliminating most... accident initiators (for example, large pipes in primary circuit), by improving decay heat removal and including more efficient passive heat removal from reactor vessel, more in-factory fabrications, transportability and site selection flexibility, smaller plant footprint and use of seismic isolators for increased seismic safety" [44]. One advocate for a fast neutron based SMR has commented that many existing plants can never be adequate safe because the "confined capability of the first nuclear power plant generations to withstand severe accidents" whereas SMRs provide "sure protection against all severe accidents" [69]. This "safety-by-design" approach, it is argued, can focus on "eliminating by design the possibility for an accident to occur, rather than dealing with its consequences" [70].

A second feature that is argued to ameliorate the risk of accidents is the fact that SMRs have reduced their "total power output to the relatively low level of 300 MW (thermal), compared to the more typical 1000–3000 MW (thermal) capacity of large-scale nuclear stations greatly reduces the amount of thermal energy that must be removed with emergency core cooling measures in accident conditions" [71].[8] In other words, even if a Fukushima like situation were to occur, the amount of heat that needs to be pumped out of the reactor is much smaller.

The third factor that has been emphasized as a safety enhancing characteristic is "reliance on passive features" [73–75].[9] Designers of the SVBR-100, a modular fast reactor with an eutectic lead-bismuth alloy as coolant, argue that "the most expedient way to upgrade [nuclear power plant] safety that simultaneously improves the [nuclear power plant] economic characteristics is use

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[7] Former U.S. Secretary of Energy Steven Chu described himself as a "big fan" of SMRs in part because they "can be shipped internationally. [A] very very big deal" [65].

[8] Likewise, analysts from General Atomic also stress that the EM^2 has "improved safety due to smaller core size" [72]. Note that a thermal power output of 300 MW implies that the electrical output would only be of the order of 100 MWe.

[9] At the same time, it must be pointed out that there remain questions about the reliability of using passive features to assure safety. As the IAEA pointed out: "Reliability of passive safety systems may not be understood as well as that of active safety systems" and that "There may be a potential for undesired interaction between active and passive safety systems; It may be more difficult to 'turn off' an activated passive safety system, if so desired, after it has been passively actuated; Implications of the incorporation of passive safety features and systems into advanced reactor designs to achieve targeted safety goals needs to be proven, and the supporting regulatory requirements need to be worked out and put in place" [129].

of reactor facilities, in which the value of the stored potential energy is the lowest and in which the inherent self-protection and passive safety properties can be realized to the maximal extent, for example on the basis of SVBR-100" [74].

Engineers often evaluate the safety of a design using the Probabilistic Risk/Safety Assessment/Analysis (PRA/PSA) methodology. This methodology conceives of accidents as resulting from one of many combinations of a series of failures, and computes the probability of a severe accident resulting from these.[10] Using such models, and presumably based on the above-mentioned factors, reactor designers, vendors, and regulators have made claims about the frequency of severe accidents at various reactors, usually expressed in terms of a core damage frequency (CDF).[11] SMR designers estimate CDFs in the range of 10^{-5} to 10^{-8}, comparable to or lower than modern LWRs [43].

Proponents of SMRs believe that these "inherent safety properties" will enable "a high level of social acceptability" [77].[12] Likewise, in its presentation to the Leadership in Nuclear Energy Commission of the state of Idaho, the Director of Business Development of Generation mPower, promised to "develop and deploy, by 2020, an SMR that. . .is [seen as] benign. . .[with] public acceptance" [79]. An IAEA technical document observes that "innovative reactors aim to eliminate the need for intervention in public domain", and there would be no need to require emergency planning procedures [80]. All of these are intended to address yet another challenge confronting nuclear expansion: public resistance to reactor construction [81–83].

Easing of nuclear waste problem, especially dealing with transuranics (chemical elements that have an atomic number greater than that of uranium), is yet another promise of some SMRs, specifically SMRs based on fast neutrons. One paper, for example, argued that the "elimination of long-lived radioactive wastes" could be "quite realistic" with SMRs, leading to a "long-lived waste free strategy" [84]. Similarly, General Atomics argues that "today's fission technology cannot" meet energy security needs "without adding to the ever-increasing volume of high-level waste; these waste concerns may be the limiting factor in the use of nuclear power" and "in an attempt to allow nuclear power to reach its full economic potential, General Atomics is developing the Energy Multiplier Module (EM^2). . .[in which] waste problems are mitigated by several factors: higher burnup, fuel use in multiple generations, and conversion of existing waste to energy" [85].

Yet another arena stressed by SMR proponents is "enhanced proliferation resistance and increased robustness of barriers for sabotage protection" [86]. The EM^2 reactor is said to have enhanced proliferation resistance "because no enrichment is required beyond that needed for the first generation fuel load" [85]. SMR advocates also expect that these "reactors will operate without on-site refueling or will have long periods between refueling using well-contained fuel cassettes that would impede clandestine diversion of nuclear fuel material" [86]. An example of a proposed design that seeks to avoid on-site refueling is the Atoms For Peace Reactor [71,87]. According to its developers, the design explicitly "incorporates a 20+ year core life requirement to enhance the proliferation resistance attribute associated with reactor" [71].

The possibility of such long-lived cores has led some analysts to propose a hub-and-spoke arrangement whereby these reactors are manufactured in a few internationally controlled and well-protected locations, where all fuel cycle services would be located as well. The reactors would be transported to user locations, operated for the duration of their fuel charge, and then returned to the manufacturing location for refueling by the international consortium that produced them [42,88,89].

3. SMR families

To simultaneously deliver lowered costs, increased safety, reduced waste, and enhanced proliferation resistance sets a very high bar for SMRs designs. The question is whether existing SMR designs can realize all of these goals? Answering this question is not straightforward. There are a very wide variety of SMR designs with distinct characteristics that are being developed. These designs vary by power output, physical size, fuel geometry, fuel type and enrichment level (and resulting spent fuel isotopic composition), refueling frequency, site location, and status of development. To make some sense of the different designs, Alexander Glaser has proposed that they be categorized into four families [90].

The first family of SMRs involves reactor designs that will likely be the earliest that would be introduced into the market.[13] The idea guiding these designs seems to be to "get into the game early" [90]. These are essentially standard but scaled-down light water reactors, usually with steam generators located within the same pressure vessel as the reactor itself (integral Pressure Water Reactor or iPWR).[14] Integration of the primary system has been assessed by some analysts to be "the biggest challenge to SMR development" [92]. These reactors are typically fueled with low enriched uranium, with enrichment levels of 5% or less. Not only is the enrichment of fuel in the same ballpark as conventional light water reactors, but even the fuel assembly designs are intended to be almost identical to existing designs (although scaled down in height).[15] Because of the similarity of the fuel design, the spent fuel can be reprocessed using traditional and widely understood techniques such as PUREX.

A second family of SMRs involves a design that has been around for a long time, the high temperature gas-cooled reactor (HTGR).[16] These are often viewed as a source of both electricity and process heat for industrial purposes.[17] The hope for designers of these

[10] There are serious problems with the probabilistic risk assessment methodology and there are good reasons to believe that severe accidents will be far more frequent than quantitative tools such as probabilistic risk assessments predict [76]. Nevertheless, for a variety of sociological reasons, such risk assessments are considered credible by policy makers [16].

[11] There are no fully documented probabilistic risk assessments for SMRs available in the public domain; so it is not possible to know what goes into these claims or how reliable these are. Further, many SMR designs are far from final and are still undergoing modifications.

[12] Others point out that there is "general opposition of part of the population to any form of nuclear energy" and the "larger number of plants" required if SMRs are deployed in place of current reactors would impede their deployment [78].

[13] Note, however, that earliest does not necessarily mean soon. Even optimistic estimates of the deployment period indicate that a decade or more would pass before SMRs begin to be deployed. More realistic evaluations would suggest even longer periods. Such timelines, however, reduce the commercial attractiveness even further. Indeed, as one analyst argues, "On past evidence, the chances that any of these new designs will become commercially available seem low" [91].

[14] Examples of reactor designs within this group include W-SMR (Westinghouse), mPower (Babcock & Wilcox), NuScale (NuScale Power), SMART (KAERI), ACP-100, and HI-SMUR 140 (Holtec).

[15] As a Westinghouse presentation to the U.S. Nuclear Regulatory Commission put it, the objective of the company's "fuel design program is to minimize licensing risks" and therefore it is basing its fuel design on "currently operating designs with significant operating experience" involving the use of "currently developed fuel assembly core components as much as possible" and reliance on "currently used design processes and procedures" [93].

[16] This type includes the HTR-PM (China National Nuclear Corporation), GT-MHR (General Atomics), and ANTARES (Areva).

[17] The remark by Georges Serviere, EDF Generation vice president for nuclear engineering, at a 2003 hearing of the French parliament's office of technology assessment (Opecst) in Paris, is a good indication of how many utilities view gas cooled reactors. Serviere said that France is more likely to need "rather big" reactors and, that small HTRs like the South African Pebble Bed Modular Reactor or the

reactors seems to be to "succeed the second time around" after earlier failed attempts at commercializing similar designs.[18] These reactors typically use uranium enriched to well above 5 percent as fuel, and graphite as a moderator. Helium or carbon dioxide is often used as the coolant fluid. The fuel for these reactors is usually in the form of TRISO (tristructural-isotropic) particles, which consist of uranium coated with multiple layers of different materials that can withstand high temperatures and are hard—but not impossible—to reprocess.

The next category of reactors attempts to "deal with the waste legacy" while extending uranium resources by using uranium much more efficiently.[19] Reactors in this group are based on the use of fast neutrons without any moderator and may have long-lived cores, which are designed not to require refueling for two or more decades and may be helium or sodium-cooled. The distinguishing feature for this group is their usage of spent nuclear fuel or nuclear waste or weapon-grade plutonium as a fresh fuel.

Lastly, there are designs with long-lived cores that are designed for possibly unattended operation. The idea motivating designers seems to be to "offer nuclear batteries" [90]. They are generally targeted at "newcomer" nations with small electric grids interested in developing nuclear power systems or remote locations in developed countries.[20] These reactors tend to be liquid metal-cooled fast reactors with high enrichment levels required for fresh fuel (for example, although not a fast reactor, the KLT-40S uses fuel enriched to close to 20 percent).

4. Choices and conflicts

The reason that it is not straightforward to evaluate SMRs in general against desired criteria is that the different designs described in the previous section have different characteristics. Specific design characteristics often address one or more of the motivations mentioned above, but it is not always possible to address all desirable criteria simultaneously.

Further each of these criteria has several dimensions, and multiple technical characteristics are needed to effectively implement each criterion. The economics of nuclear power, for example, is a challenge both because of the high cost of constructing each facility and the high cost of generating each unit of electrical energy relative to other options for meeting the same demand. The two are related but distinct. As we shall see, even if SMRs might ameliorate the first challenge to some extent, they might make the latter challenge even harder to meet. Conversely, a large energy project might produce lower cost electricity relative to a small power plant but might have difficulty getting off the ground because of the high initial expenditures.

The challenge of disposing of highly radioactive waste is addressed partially by reprocessing spent fuel, which reduces the volume of the most highly radioactive waste stream but only by increasing the volumes of waste streams with lower levels of radioactivity enormously. Reprocessing is also much more expensive than direct disposal of nuclear waste [96–98], exacerbating the economic challenges of nuclear power. SMRs could further accentuate the waste disposal challenge.

Proliferation resistance is another characteristic that imposes contradictory requirements. One way to lower the risk of diversion of fuel from nuclear reactors is to minimize the frequency of refueling because these are the periods when the fuel is out of the reactor and most vulnerable to diversion. In a reactor that is under safeguards aimed at lowering the possibility of such diversion, the refueling is monitored. However, since safeguards are not perfect, proliferation resistance would be increased when such refueling is minimized. Therefore, many SMR designers seek longer periods between refueling. However, in order for the reactor to maintain reactivity for a longer period, it would have to start with fresh fuel with higher uranium enrichment or plutonium. Some designs even call for going to an enrichment level beyond 20 percent of uranium-235 [99], usually considered a threshold for classifying material as potentially useable in a weapon. All else being equal, the use of fuel with higher levels of uranium enrichment or plutonium would mean a greater chance of proliferation. The proliferation could occur through diverting fresh fuel or at the enrichment plant. Thus, the reduction of proliferation risk at the reactor site is accompanied by an increase in the proliferation risk elsewhere. Quantitative techniques are not sufficiently reliable to make quantitative comparisons of these two risk factors.

We now lay out some of the key conflicts between multiple priorities.

4.1. Safety and economics

The standard approach to lowering the probability of a catastrophic nuclear accident involves the use of multiple redundant safety features in the design of the reactor. The second aspect of safety that many reactor designs stress is the use of features that could mitigate the impact to the public from an accident, should one occur. Together these features are often termed "defense in depth" [100,101].

As described earlier, SMR designers have tried to lower the risk of accidents through various design choices, an important one being the power capacity of the reactor. All else being equal, a lower power reactor implies a smaller inventory of radioactive material in the core and less energy available for release during an accident. The first characteristic implies that there is less material on the whole available for dispersal during an accident; the second characteristic implies that a smaller fraction of this material will likely be dispersed during an accident.

The price for this smaller size is that there are diseconomies of scale. In industrial engineering, a general rule of thumb says that the capital costs of production facilities scale as the 0.6 power of the size of the facility [102]. That is, if there are two plants of size S_1 and S_2, the ratio of their capital costs are related as:

$$\frac{K_1}{K_2} = \left(\frac{S_1}{S_2}\right)^{0.6}$$

This implies that, all else being equal, an 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

General Atomics-inspired Gas Turbine-Modular Helium Reactor do not, in themselves, present advantages for the French market, but can be seen as "paths to very high temperature reactors or gas-cooled fast reactors" which are more apt for non-power applications [94].

[18] The most recent and prominent failure is that of South Africa's experience with trying to commercialize the pebble bed modular reactor (PBMR). The PBMR Limited was established in 1999 with the stated intention, according to its website, "to develop and market small-scale, high-temperature reactors both locally and internationally" [95]. The company claimed that the PBMR technology had "numerous advantages including safety, reliability, cost effectiveness, modularity and a minimal carbon footprint", all of which should be familiar from our earlier discussion. PBMR also appealed to nationalist sentiments and its website proclaimed that the company was "proudly South African" [95]. Eventually, after a dozen years and the expenditure of a considerable amount of public money, the attempt was abandoned, thus negating, in essence, many of the claimed advantages, especially cost effectiveness [45].

[19] Examples of this family include waste or plutonium burner reactors such as EM2 (General Atomics), PRISM (GE-Hitachi), and TWR (Terrapower).

[20] This family includes the Gen4 Module (G4M) (Gen 4 Energy, formerly known as Hyperion), 4S (Toshiba), and the SSTAR (Lawrence Livermore, Los Alamos, and Argonne National Laboratories).

would generate only 20 percent of the electricity. Thus, the 200 MW SMR has roughly twice the cost per kW of capacity, and this directly translates into a higher cost per unit of electricity generated.

The argument offered by SMR proponents is that this scaling rule does not apply because SMR designs are quite different from traditional designs. Further, they argue that the economic advantages accruing from modular and factory construction, learning from replication, and co-siting of multiple reactors will compensate for any diseconomies of scale [103]. Other non-financial factors, such as siting and grid constraints, and impact on the national industrial system, are also claimed to influence decision making significantly and SMRs, according to their proponents, score high on these factors [60]. Another argument proffered for SMRs is that they are a "suitable choice" when the "social aspects of the investment, such as the creation of new employment positions, is a goal of policy makers" [104]. Since no SMRs have been manufactured, it is not possible to reliably evaluate these arguments.

However, the rhetoric about the many sources of potential savings notwithstanding, many, including personnel from major US reactor vendors that are actively developing commercial SMRs, do not believe that SMRs would be able to compensate for the diseconomies. A detailed expert elicitation study involving people "from, or closely associated with, the nuclear industry" revealed that most experts predict higher costs per kW of capacity than currently operating reactors [105]. Other expert elicitations come to similar conclusions [106]. Note that this is only comparing SMRs with currently constructed GW scale reactors; they would fare even more poorly if compared with other sources of electricity such as coal and natural gas based thermal plants widely seen as the chief energy technology competitors to nuclear power.

In addition to the diseconomies of scale, there are other technical features of SMRs that affect their economics. As discussed earlier, SMR safety benefits from the size of the reactor because of the increased surface area to power ratio when compared to larger reactors. This characteristic increases the area available to transfer heat from the core [92]. But the same feature also increases the rate at which neutrons escape from the reactor core, which, in turn, reduces the amount of energy generated per unit mass of uranium fuel (or burnup).[21] Put another way, more fuel will be needed to generate the same amount of electricity, increasing fueling costs. This is a particular problem for SMRs belonging to the first family [107].

Some SMR designs adopt special features to allow for a high burnup while maintaining safety. An important example of these are reactors of the second family, such as the HTR-PM, that require the use of fuel in the form of small balls (pebbles) with special coatings that can withstand the high temperatures that could be reached in the reactor core without allowing fission products to escape. While this enhances safety, the associated fuel fabrication costs more than the corresponding fuel fabrication for light water reactors because of the use of "more expensive materials and non-conventional production process" [104].

Another feature that SMR designers propose to incorporate into reactor construction is to place the main parts of the reactor complex underground. All the leading first family designs in the United States propose to do so [105]. While underground construction could reduce some risks, it could create new problems as well, such as aggravating the problem of flooding [108]. But what's more relevant to our discussion of the tradeoffs is that it will likely result in higher capital costs, longer construction periods, and an overall increase in operation and maintenance costs; a study of underground construction for a CANDU reactor, which is larger than SMRs, but smaller than current generation LWRs, suggested a capital cost increase of 31–36 percent, and a 16-month increase in the construction period [109].

If SMRs have these inherent economic challenges that result from their technical features, SMR vendors and utilities considering their construction are contemplating choices that might deliver cost savings but only at the expense of safety. This has become evident in the ongoing effort by SMR proponents to have regulators weaken various prevailing safety standards as part of seeking licenses [46]. We list two examples below.

One of the concerns that most nuclear agencies around the world articulated in the aftermath of the Fukushima accidents was to emphasize the need for more sources of local power in the event of a failure of the electrical grid. The inability to supply electricity to the water pumps was one of the primary precursors to the loss of cooling at the Fukushima Daichi reactors, and this ultimately led to the fateful accidents.

In contrast, many SMR vendors would like to avoid installing diesel generators and other sources of emergency power. For example, Babcock and Wilcox posits that because it relies on passive safety, "emergency diesel generator power [is] not required" [110]. Likewise, NuScale promises that it has no need for pumps or for emergency generators because of inherently safe natural circulation of water [111]. The main motivation for avoiding installation of such devices appears to be to lower costs.

Another area where SMR advocates seek to advance economics over safety is over the size of the emergency planning zones. At Fukushima, the chairman of the U.S. Nuclear Regulatory Commission called for evacuation up to 50 miles. Thus, it would seem to be prudent to plan for how to carry out potential evacuations in the event of a major accident.

Many SMR designers, on the other hand, would like to avoid such planning altogether.[22] For example, one risk-related goal of the now-abandoned IRIS reactor designed by Westinghouse was "to reduce the Emergency Planning Zone (EPZ) to within the exclusion area by demonstrating that the off-site doses are consistent with the US Protective Action Guidelines (PAGs) for initiation of emergency response, so that the required protective actions would be limited to the exclusion area" [113].

If nuclear regulators allow the relaxation of current safety requirements while licensing SMRs, it would imply an overall reduction in safety.

4.2. Waste reduction and proliferation risk

One way that designers have tried to reduce the quantity of radioactive waste generated has been to move to reactors that use fast neutrons.[23] Because a significant fraction of their energy is released through the in situ breeding of fuel, fast reactors do require far less uranium to be loaded and produce less nuclear waste. Even in those cases where the spent fuel unloaded from such an SMR

[21] The burnup is further lowered by a design choice. In order to reduce the time lost in refueling, vendors of iPWRs often eschew shuffling of fuel elements within the core and adopt a fuel management scheme wherein the whole core is replaced at the same time.

[22] The IAEA in fact advertises a "reduced emergency planning zone" as a perceived non-technological advantage for SMRs [112].

[23] Broadly speaking, one can classify reactors into two categories: thermal and fast. In thermal reactors, the core contains some light material like water or heavy water or graphite. When the neutrons produced by fission reactions interact with these materials, they lose energy and become slower, i.e., they thermalize. In fast reactors, as the name implies, the neutrons remain fast and energetic because there is no such light material to slow them down. Of course, eventually these neutrons do interact with another fissionable nuclei or reactor components or escape from the core.

is not reprocessed and ultimately prepared for final disposal, the quantity of waste generated would be significant reduced [107].

The total amount of plutonium generated with these designs, however, is *much* larger than for light water reactors. More importantly, the concentration of plutonium in the spent fuel is about 6–7 times higher than in LWR fuel. This characteristic translates directly into a higher risk of proliferation because would-be proliferators have to divert only a much smaller quantity of spent fuel to a clandestine reprocessing plant to produce adequate material to make one or more nuclear weapons.

Proponents of such SMRs usually claim that their designs are proliferation resistant because the plutonium in the spent fuel is not separated out routinely. However, this assertion assumes that the reactor and spent fuel are used as intended, and does not account for misuse or diversion. Indeed, the very definition of proliferation resistance from the IAEA—characteristics of a nuclear energy system that impede the diversion of undeclared production of nuclear material or misuse of technology by states in order to acquire nuclear weapons or other nuclear explosive devices [114]—involves the possibilities of misuse and diversion.

Further, despite the higher costs associated with reprocessing, there are many countries that persist with reprocessing spent fuel, including Russia and India. Many other countries have ambitious plans to embark on reprocessing. Further, outside of the United States, most fast spectrum SMRs are being designed to operate in a closed fuel cycle [43]. The high concentration of plutonium will make the reprocessing of spent fuel from SMRs that much more economically attractive. Reprocessing has traditionally been associated with greater proliferation risks and thus the widespread of adoption of the technology would enhance the risk of nuclear weapon proliferation.

4.3. Waste reduction and safety

The use of fast neutron reactors to reduce the amount of waste generated also has implications for safety. In thermal reactors, the core is typically in its most reactive configuration when it is operating normally at full power. Any change to this configuration in an accident would therefore decrease the power being produced. In fast reactors by contrast, collapsing the fuel into a reduced volume increases the rate at which the chain reaction occurs. If this were to happen quickly enough, the pressure in the fuel would rise fast enough to lead to an explosion. This could fracture the protective barriers around the core, including the containment building, and release large fractions of the radioactive material in the reactor into the surroundings. Such a “core disassembly accident” (CDA) has therefore been an important concern among the fast reactor design community ever since the first fast neutron reactors were constructed [115]. CDA studies have been conducted for nearly all of the fast reactors constructed or proposed in the United States and Western Europe [116]. Core meltdown accidents can also occur without disassembly: two U.S. fast reactors have had partial core meltdowns.

Another safety problem that affects some fast reactors, including SMRs, is due to the use of molten sodium as coolant. Though sodium has some safety advantages, it reacts violently with water and burns if exposed to air.[24] Further, when sodium absorbs a neutron, it is converted to an intensely radioactive isotope called sodium-24, a major problem when any component in the reactor has to be repaired. One of the persistent problems in sodium cooled fast reactors built so far has been the propensity for leaks to develop, especially in the steam generators. These have occurred in almost all countries and at various stages of the operational life, suggesting that there are fundamental reasons for such leaks [117]. These safety problems are likely to afflict SMRs that are based on the same principles as well.

[24] Accordingly, the molten sodium always has to be covered by an inert gas, such as argon, which in turn tends to get swept into the flowing sodium and cause unwanted bubbles.

4.4. Proliferation resistance and economics

As discussed earlier, one avenue that has been pursued by SMR designers to improve proliferation resistance is through increasing the period between refueling. A good example of a reactor design that seeks to achieve greater proliferation resistance is the Atoms for Peace Reactor (AFPR-100). AFPR-100 is a 100 MW(e) reactor that was originally designed to have no need of on-site refueling [87]. Over the years, however, its design has been evolving (in part because of problems with the fuel that had not been envisaged) and therefore cannot be treated as finalized.[25]

The longer lifetime of the fuel—in this case, designed to be the lifetime of the reactor itself—comes at a price: increased fueling cost. The problem is that the operator of the reactor would have to pay upfront for two or three decades' worth of fuel rather than being able to pay for annual or biennial loading of fuel at a time. A second factor driving up the cost is the higher uranium enrichment level needed to keep the reactor working through its lifetime. Together, these render the cost of fueling the reactor much more expensive. For example, the average enrichment level of fuel for the AFPR was about 11.3 percent [118]. This could result in a cost for uranium enrichment and fuel fabrication to be about $8000/kg as opposed to about $2500/kg for 4% enriched uranium. The total premium for the use of a larger upfront loading of uranium with higher enrichment depends on the details of the design, but we estimate that it could be of the order of $30/MWh more than a conventional LWR. This is a substantial economic disincentive.[26] The case of “nuclear battery” type SMRs is likely to be similar.

5. Technical characteristics and consequences

Because of the multitude of SMR designs that are being developed, it is hard to make generic statements with wide applicability. At the same time, these different designs do have some shared technical characteristics, and these characteristics affect how these reactors might score on different desirable criteria. Table 1 summarizes some of the shared technical characteristics and their impacts.

The smaller power capacity of SMRs has a largely negative effect on costs. It is possible that this negative effect could be offset somewhat through economies of mass manufacture or by regulatory authorities relaxing licensing rules. But, like many experts whose views on the subject have been elicited, it seems to us unlikely that the offsetting would be sufficient to make these reactors economical. In addition, there are specific features of each of these SMR types that would tend to increase costs. For example, the lower

[25] The initial proposal was to use TRISO fuel elements, somewhat like high temperature reactors of the second family. However, these were found to undergo significant swelling in the silicon carbide fission product barrier coating layer when the fuel is irradiated. To deal with this problem, the reactor's designers have proposed using a Spherical Cermet Fuel element. Cermet refers to composite materials that are composed of ceramic (cer) and metallic (met) materials. This new Cermet fuel concept, however, will reduce the core lifetime by about 3.1 Effective Full Power Years, in other words increase the refueling frequency. Therefore, there is a conflict between trying to meet the two criteria of increasing proliferation resistance and operational safety (which is impaired by fuel swelling) simultaneously.

[26] The US Department of Energy's Energy Information Administration estimates the total levelized cost of electricity from new nuclear reactors to be about 108 $/MWh [119].

Table 1
Generic SMR designs and the relationship of technical characteristics to various desirable goals; the implicit comparison is with standard-sized light water reactors.

SMR family	Technical characteristic	Desirable criteria			
		Cost	Safety	Volume of waste	Proliferation risk
iPWR	Smaller size, lower fuel burnup	Higher	Increased	Larger	Increased
HTGR	Lower power density and higher enrichment level	Higher	Increased	Mixed impact	Mixed impact
Fast Reactors	Higher power density and higher fissile content, molten metal coolants	Higher	Decreased	Smaller	Increased

fuel burnup in iPWRs means that fueling costs would be higher whereas the special materials used to coat the fuel particles in high temperature reactors and non-conventional manufacturing techniques also lead to higher fueling costs. The small physical size and smaller fissile inventories of SMRs, on the other hand, benefits safety. However, in the case of fast reactors, there are other characteristics that affect safety negatively. These include the potential in the core for accidents involving disassembly and reactivity increase as well as the use of molten metals as coolants. Proponents of these reactors argue, not surprisingly, that they are safe, but the use of fast spectrum neutrons and molten metal coolants is a significant disadvantage from a safety perspective.

The use of fast neutrons for these reactors is primarily motivated by waste reduction not safety. Indeed, SMRS based on fast neutrons do produce a lower amount of radioactive waste per unit of electricity generated. The significance of the lower rate of waste generation, however, is debatable. The problem with siting geological repositories for waste disposal has been local and public resistance. The level of resistance is not particularly sensitive to the amount of waste that might be disposed of in the repository. In other words, even if the repository were to be designed to deal with a significantly smaller volume of spent fuel, there may not be a corresponding decrease in opposition to siting the facility.

Proliferation risk depends on both technical and non-technical factors. While the non-technical factors are largely not dependent on choice of reactor type, SMRs and their intrinsic features do affect the technical component of proliferation risk. In the case of both iPWRs and fast reactors, the proliferation risk is enhanced relative to current generation light water reactors primarily because greater quantities of plutonium are produced per unit of electricity generated. In the case of HTRs, proliferation risk is increased because of the use of fuel with higher levels of uranium enrichment, but is diminished because the spent fuel is in a form that is difficult to reprocess.

6. Conclusion

Proponents of the development and large scale deployment of small modular reactors suggest that this approach to nuclear power technology and fuel cycles can resolve the four key problems facing nuclear power today: costs, safety, waste, and proliferation. All the concerns about economic competitiveness, waste generation, avoiding catastrophic accidents and nuclear proliferation are fundamentally social in origin. The solution attempted by nuclear developers and vendors is to encode these priorities into the design of a specific nuclear reactor.

The technical reality, however, is that each priority drives the requirements on the reactor design in different, sometimes opposing, directions. Our survey of the characteristics of the different SMR designs under development suggests that none of the designs meet all four of these challenges simultaneously. Most, if not all designs, involve tradeoffs and addressing one of the four problems, for example cost reduction, involves choices that make one or more of the other problems worse.

What then explains why many, including policymakers and even some environmentalists, have invested so much hope in the vision of SMRs solving all the problems confronting nuclear energy? A fully adequate explanation necessarily has to turn to other, cultural and political, factors. We turn to these briefly.

The nuclear industry sees and seeks to present SMRs as the same but different from previous reactors. Partly because of their reliance on earlier designs and their smaller size, SMRs offer "connotations of familiarity and controllability" [120]. The industry would like communities to be even more familiar with them through, for example, siting them close to population centers. One youtube video explains how each town could have its own SMR, or possibly more than one as the town grows, and which "might not even impact your view" because they would be constructed underground [121]. Media commentators routinely invoke the maxim popularized by the economist E. F. Schumacher, "small is beautiful", in part to try and gain greater public acceptability (for example, [122]). And, finally, as the latest incarnation in a long list of finally-perfect reactor concepts, SMRs also appeal to a traditional source of support for nuclear power: the association with modernity [26,123,124].

A primary reason for the attraction of SMRs to many has been concern about climate change. The cultural and political assumption, usually unstated, that underpins many searches for solutions to climate change within the dominant culture is that there is no social possibility of stopping the continued growth in energy demand let alone reducing it drastically. This has led to a "compulsive" search for what has been aptly termed the "abundant energy machine" [125], with the only constraint being that the chosen technology produce energy with a low level of carbon dioxide emissions.

Though renewable energy technologies and energy efficiency measures are popular and many do see them as a partial, if not whole, solution to climate change, there are a variety of cultural and institutional barriers to wider use of these, especially in the United States [126]. In part because of these barriers, environmentalists and policy makers have dismissed the possibility of dealing with climate change solely through the adoption of renewable energy sources and energy efficiency measures. At the same time, ideas and hopes about nuclear power as a possible solution to climate change have been "deeply constituted by incumbent interests" [127].

The rhetorical claims made by purveyors of SMRs offer a way for pro-nuclear environmentalists and policy makers to argue that the challenges that confronted earlier generations of large reactors do not apply to SMRs, thus allowing the possible imagination of a different nuclear powered future.

SMR advocates go one step further; they offer a range of powerful and compelling fantasies involving the technology [128]. These fantasies are associated with promises to aid the achievement of environmental and developmental goals, such as solving the problem of nuclear waste and producing cheap electricity and drinking water for the poorest populations of the world, while simultaneously avoiding the known accident risks associated with nuclear technology. Thus, for example, rather than talking about the electricity market, the CEO of one SMR firm highlights the challenge of providing clean water as the driving motivation for his attempt to commercialize a small reactor [120]. SMRs, therefore, position themselves as simultaneously solving not just all the challenges confronting nuclear power but also as vehicles to a number of other desirable goals.

SMR fantasies are "*selective* [and] choose what aspects history to highlight and leave out potential challenges to their vision as if they simply did not exist" [128]. In particular, these fantasies serve as a way to get around the fact that the annals of nuclear power include a long and painful record of failed promises. The mismatch between the technical characteristics of SMRs and prevailing—and sometimes competing—social priorities suggests that SMRs may become another chapter in this history.

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