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Expert Judgments about RD&D and the Future of Nuclear Energy

Laura D. Anadón,[†,*] Valentina Bosetti,[‡] Matthew Bunn,[†] Michela Catenacci,[‡] and Audrey Lee[†,§]

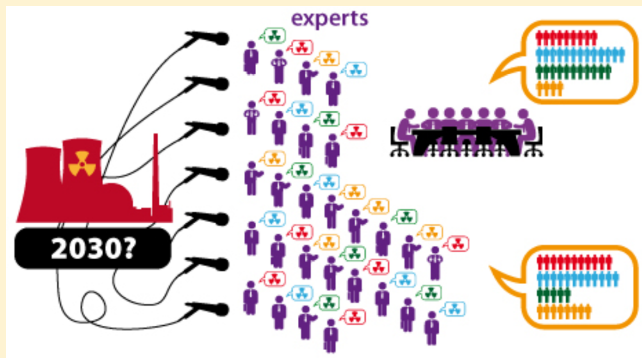
[†]John F. Kennedy School of Government, Harvard University, 79 John F. Kennedy Street, Cambridge, Massachusetts, 02138, United States

[‡]Fondazione Eni Enrico Mattei, Corso Magenta 63, 20123, Milan, Italy

[§]California Public Utilities Commission, 505 Van Ness Avenue, San Francisco, California, 94102, United States

Supporting Information

ABSTRACT: Probabilistic estimates of the cost and performance of future nuclear energy systems under different scenarios of government research, development, and demonstration (RD&D) spending were obtained from 30 U.S. and 30 European nuclear technology experts. We used a novel elicitation approach which combined individual and group elicitation. With no change from current RD&D funding levels, experts on average expected current (Gen. III/III+) designs to be somewhat more expensive in 2030 than they were in 2010, and they expected the next generation of designs (Gen. IV) to be more expensive still as of 2030. Projected costs of proposed small modular reactors (SMRs) were similar to those of Gen. IV systems. The experts almost unanimously recommended large increases in government support for nuclear RD&D (generally 2−3 times current spending). The majority expected that such RD&D would have only a modest effect on cost, but would improve performance in other areas, such as safety, waste management, and uranium resource utilization. The U.S. and E.U. experts were in relative agreement regarding how government RD&D funds should be allocated, placing particular focus on very high temperature reactors, sodium-cooled fast reactors, fuels and materials, and fuel cycle technologies.



INTRODUCTION

Nuclear power may prove to be one of the key technologies the world uses to respond to climate change, but it faces many challenges. Integrated assessment models of future energy and climate paths vary widely in their projections of future nuclear energy growth.[1−3] Studies that place no constraints on nuclear energy tend to project very large-scale growth, with nuclear energy providing a significant fraction of future carbon reductions.[3] But nuclear energy's growth in recent years has been very modest, with roughly four reactors per year connected to the grid worldwide on average in the past decade.[4] Growth has been constrained by high costs and a variety of political, regulatory, and public acceptance challenges, which are likely to be exacerbated by the reaction to the Fukushima accident in Japan. For nuclear power to displace a billion tons of carbon a year by 2050, roughly a tenth of what is likely to be needed to meet the internationally agreed goal of limiting global average temperature increases to 2°C above preindustrial levels, would require adding 25 large nuclear plants to the grid every year from now until 2050.[5] This means nuclear energy would have to become much more attractive to those making decisions about what types of power plants to build than it was in the decade before the Fukushima disaster.

Development of improved nuclear technologies, offering lower cost or improvements in areas such as safety, security, proliferation-resistance, uranium resource utilization, and waste management could address some of nuclear energy's challenges, whereas others may be dependent on policy and political factors. These nontechnological constraints may be affected by unpredictable events such as another large nuclear accident, a terrorist attack on a nuclear facility, or successes in siting and building geologic repositories for nuclear waste.

Decisions on research, development, and demonstration (RD&D) investments, technology subsidies, and the like could be improved with better information on how the cost and performance of key technologies might change in response to such investments. This paper provides detailed assessments from a range of U.S. and European technology experts of the expected future cost and performance of three classes of nuclear reactor systems, large light-water reactors similar to those currently available on the market (known as Gen. III/III+ reactors), the next generation of designs (Gen. IV), and small modular reactors (SMRs) with sizes below 300 MWe. It also presents these experts' judgments of how much governments should spend on nuclear R&D, how those funds should be

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allocated, and what benefits such investments might bring in improving nuclear energy cost and performance.

Because the future of technology is inherently uncertain, it is crucial to collect not just best estimates but judgments about the likelihood of a range of outcomes. Such distributions cannot be derived merely by looking at how a particular technology has evolved in the past, or through simple learning-curve models.[6]

When past data is unavailable or of little use, the alternative is to rely on subjective probability judgments.[7] For decades, many studies have solicited experts' subjective judgments of the probability of uncertain events, for use as an input to the decision-making process.[8−10] However, both collecting estimates from experts and integrating these estimates into the decision process present important challenges.[11] As we discuss in the next section, it is important to structure the elicitation instrument to reduce overconfidence and other biases, thereby improving the quality of the estimates.[8,10,12−16]

■ MATERIALS AND METHODS

Expert elicitations are used to collect the views of experts individually, which means that experts do not have the opportunity to develop increased consensus through discussion among the experts. Group-based methods such as the Delphi process[17] can sometimes be unduly influenced or distorted by the views of a small portion of the experts or by social interactions. To explore the potential value of government-funded research, development) investments in addressing the challenges facing nuclear energy, we undertook a novel two-phase expert elicitation combining both individual interviews (conducted in an interactive online format) and a group meeting.

There are several prior studies using expert elicitations on the future of energy technologies,[18−22] though our online protocol is unusual. Similarly, there are several studies that have used structured group-based elicitation methods,[23,24] as well as cases in which a preliminary workshop has been organized before the individual interviews to help survey design.[25] But we are not aware of any instances in which individual elicitations were followed up by a group workshop, giving experts a chance to discuss and revise their answers. We combined the two approaches because the literature suggests that individual elicitations are the most suitable approach for obtaining detailed quantitative data from experts,[14] as this method avoids biases stemming from group dynamics (e.g., social pressure[26]) and because conversely, group thinking and open discussion can help experts move away from individual anchors and prejudices. The proposed combination of both methods ensured that each expert answered independently and, at the same time, reacted to the stimulus of experts' confrontation.

The first phase of the elicitation consisted of a survey of 30 U.S. and 30 E.U. experts on nuclear technology during the summer and fall of 2010, including a cross-section of experts from private firms, government-sponsored laboratories, and academia, with experience in several countries. Ten of the 30 U.S. experts and four of the 30 E.U. experts were either in the private sector or had significant experience in the private sector. The experts included in this study have a wide range of experiences ranging from heads of nuclear units in the European Union, consultants for international organizations, directors of research centers, university professors, and chief technical officers. Some have more experience in allocating RD&D funding than others, but all are familiar with estimating the time and resources required to achieve a particular technical goal. Of course, since RD&D funding decisions require trade-offs among many objectives, their recommendations on overall funding should be considered one input among many. Given the uncertainties surrounding technical change, it is impossible to know a priori which types of experts are more likely to be correct about the impact of nuclear RD&D programs on future cost reductions and improvements in noncost factors. A large body of literature[12−14] supports the inclusion of a mix of experts in expert elicitations to obtain a wide range of views on possible technology futures, as it helps overcome the human tendency to anchor estimates to a single reference point.[13]

Resource limitations prevented us from broadening the survey to experts from Asia, Russia, and elsewhere, who should be surveyed in future work. Participating experts spent 2−5 h completing an online interactive survey. Although the literature on the use of expert judgment shows that most of the improvement in eliminating common biases is already achieved with as few as three experts,[13] the large number of reactors and of dimensions to the problem we were investigating led us to choose a much larger number of experts. Typically expert elicitations are conducted through face-to-face interviews,[14−16,19,21,28] but the online approach made it possible to elicit judgments from a much larger number of experts within time and cost constraints.

The individual online elicitation included sections with background information on current U.S. and E.U. public investments in nuclear RD&D; recent estimates of the current and future cost of different types of reactors; guidance to help experts reduce bias and overconfidence; and self-rating of expertise, among other elements.[8,10] The Supporting Information (SI) includes a list of the experts who participated in the survey and the workshop and their affiliations, links to the surveys themselves, more detail on the research protocol and the structure of the online elicitation (including the graphical strategies that were devised), and some evidence indicating that motivational biases did not play a large role in the experts' answers on budget allocation.

Experts were asked (a) for their projections of costs and performance in 2030 for the particular Gen. III/III+, Gen. IV, and SMR systems they expected to be "most commercially viable" at that time under different scenarios for government RD&D funding; (b) for their recommendations concerning how much governments should spend on RD&D, and how those funds should be allocated, by specific technology (e.g., lead-cooled fast reactor, very-high temperature reactor, fuel cycle, fuels, and materials) and by level of technology development (i.e., basic research, applied research, experiments and pilots, and commercial demonstration); (c) for their estimates of the likely results of their recommended government RD&D investments; and (d) for their views on the importance of particular factors that might constrain nuclear energy growth that are not likely to be resolved by government RD&D, including the probability and impact of particular events that could affect nuclear energy growth either positively or negatively. Wherever they were asked to make a projection about overnight capital cost, experts were also asked to provide uncertainty bounds. They were also asked to describe the main hurdles that RD&D funds would seek to address.

The Gen. III/III+ class of reactors are all light-water reactors (LWRs). The Gen. IV concepts prioritized by the Gen. IV International Forum (which our elicitation focused on) cover a wide range, including a very high-temperature gas-cooled reactor; a molten salt reactor; a supercritical water-cooled reactor; and sodium-cooled, lead-cooled, and gas-cooled fast-neutron reactors. SMR concepts include both LWRs and concepts in the Gen. IV classes. In each case, we asked experts to estimate cost and performance for the system they expected to be most commercially viable in 2030, and to specify which particular system they were referring to.

The second part of this exercise consisted of a one-and-a-half-day workshop that took place in April 2011 in Venice with a subset of 18 E.U. and U.S. nuclear experts, still spanning academia, the private sector, and national or government laboratories. The objectives of the workshop were to: (a) determine areas where consensus exists and, conversely, where the most important disputes and uncertainties lie; (b) test the validity of the information collected in the first stage; and (c) inquire about the possible reasons for differences of opinion among experts and across the Atlantic. In the workshop, experts had access to all the data gathered during the first phase, and they had the chance to discuss and compare their answers, explore the issues in greater depth, and modify their answers. The workshop occurred in the weeks immediately following the Fukushima accident in Japan, making it possible to assess how this event changed the experts' judgments.

■ RESULTS

Projected Costs of Nuclear Power. In many markets, high capital costs and associated financing difficulties are among the largest factors slowing the growth of nuclear power. Most of the experts we surveyed did not expect major breakthroughs in reducing the cost of nuclear power from any of the technologies currently in development.

The cost of nuclear energy is dominated by the initial capital costs of building the plants. We elicited estimates of the overnight capital cost, excluding owners' costs and financing costs. Actual overnight costs in the past have varied depending on how well-managed the project was, but the industry has been offering standard estimates of overnight costs of future plants assuming the projects are well-managed, and it appears that the participating experts followed this approach. Experts were asked to specify the RD&D objectives that would be addressed with the funding devoted to their top four areas, forcing experts to think through what system components would benefit most from improvements. Some experts, however, may have based their holistic projections of system costs more on the history of nuclear costs and the current perceptions of the nuclear community than on a systematic analysis of how much different cost components could be reduced. For Gen. III/III+ reactors, Gen. IV reactors, and SMRs, both E.U. and U.S. experts generally estimated overnight capital costs in 2030 greater than \$3800/kW (costs are expressed in 2010 U.S. dollars throughout this paper). As a point of comparison, a recent MIT study estimated the overnight capital cost of new Gen. III/III+ nuclear power plants in the United States at \$4000/kW installed;[29] most experts in our study offered generally similar estimates when assessing current costs.

In particular, if government RD&D spending continues at the current rate of \$466 million/yr in the U.S. and \$800 million/year in the E.U. (which we called a "business as usual" [BAU] funding scenario), half of the U.S. experts and 40% of the E.U. experts expected that the Gen. III/III+ designs would be more expensive in 2030 than they are today (in constant dollars); 25% of the U.S. experts and 19% of the EU experts thought costs would decrease modestly, with the remainder projecting that costs would stay about the same (see Figure 1). Nearly all experts projected midrange Gen. III/III+ costs of

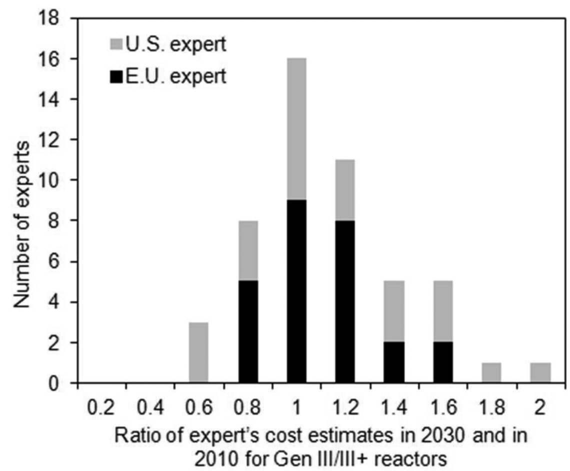

Figure 1. Distribution of experts' ratio of estimate for Gen. III/III+ capital costs in 2030 and 2010 under a BAU funding scenario.

\$3000−6000/kW in 2030 in a BAU scenario, with uncertainty ranges typically stretching from \$2000−8000/kW. Since these reactors are already designed, only a few experts projected that expanded government RD&D would reduce the cost of these systems substantially. Experts from the both sides of the Atlantic had similar estimates, although the most pessimistic bins (ratio of 2030 costs to today's costs >1.2) are slightly more populated by U.S. experts. Figure S2 in the SI shows the experts' responses on the overnight capital cost of Gen. III/III+ in 2030 under the BAU together with other RD&D funding scenarios.

While this expectation of a modest increase in cost may seem surprising, the fact is that estimates of the capital costs of nuclear power plants have been increasing steadily in recent years. Recent studies have documented a "forgetting curve" in both the United States and France (the two countries with the largest numbers of deployed reactors), with costs rising as more reactors were built.[30,31]

Only five experts out of 60 foresee a cost for the most commercially viable Gen. IV system in 2030 lower than today's Gen. III/III+ reactors, assuming current public RD&D expenditures. Figure 2 shows the distribution of experts' best estimates for Gen. IV capital costs in 2030. Experts were divided on which Gen. IV reactors would be most competitive in 2030. All of the Gen. IV designs except the supercritical-water-cooled reactor system were chosen by some experts, with the two most frequently chosen concepts being the high-temperature or very-high-temperature reactor (HTR or VHTR) systems and the sodium-cooled fast reactor (SFR) system. Figure 2 shows the uncertainty range provided by each expert; only 14 experts (one-third of the total) estimated more than a 10% chance of costs at or below a recent estimate from a team from the U.S. nuclear laboratories.[32]

Whereas the participating E.U. experts uniformly expect that the cost of Gen. IV reactors in 2030 will be higher than the cost of Gen. III/III+ reactors, the participating U.S. experts included both optimists and pessimists concerning the likely costs of Gen. IV reactors (see Figure 3). The high estimated costs of Gen. IV reactors in 2030 may be associated with the fact that most experts did not expect these systems to become

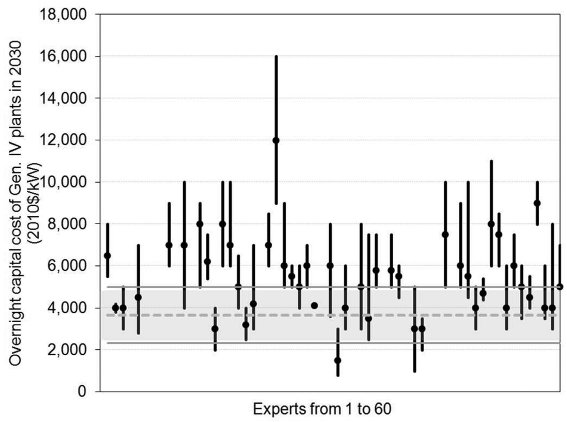

Figure 2. Experts' best estimates (black circles), and 90th and 10th percentile error bands (vertical lines) for Gen. IV capital costs in 2030 under a BAU RD&D funding scenario. The range of advanced fuel cycle (AFC) cost basis estimates is also provided for comparison (horizontal band in gray, the gray dotted line represents their best estimate).[32]

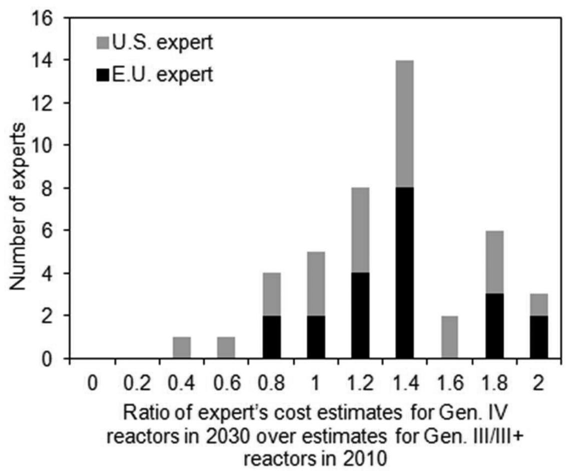

Figure 3. Distribution of experts' ratio of estimate for Gen. IV capital costs in 2030 over estimates for Gen. III/III+ in 2010 under a BAU funding scenario.

commercially viable until later dates under a BAU funding scenario, in some cases decades later (projected commercialization dates are available in the SI, section S9). In particular, over half of all E.U. experts do not expect the main European Gen. IV project to be commercialized until after 2035, whereas almost three-quarters of all U.S. experts expected some Gen. IV systems to be fully commercialized by 2030 and to have low costs (through modular design and construction and inherent features of some of the reactor systems); these factors may explain the transatlantic difference in 2030 cost projections for Gen. IV systems.

The participating experts were no more optimistic about the costs of proposed SMRs with installed capacity below 300 MWe. In a BAU public RD&D funding scenario, more than three-quarters of the U.S. and E.U. experts expected that the most commercially viable SMRs in 2030 would be more expensive in 2030 than Gen. III/III+ reactors, with almost two-thirds of the best estimates falling in the $4000−7000/kW range. Experts provided overnight capital costs of SMRs between 100 and 300 MWe, based on discussions from the workshop and comments made during the individual elicitation. Several experts made clear that their SMR cost estimates assumed a market large enough to allow mass-production in a factory. (Figure S3 in the SI shows the distribution of cost answers for SMR reactors.)

In general, most experts offered fairly wide uncertainty bounds on their projections of future costs (which is in line with the poor record of past nuclear energy cost projections), and many experts offered ranges that were skewed upward, that is, they estimated a significant chance that the cost might be much higher than their best estimate, but little chance that it would be dramatically lower.

In addition to the capital cost of building a nuclear plant, the percentage rate that has to be paid to finance such a project is also critical to the economic choice between building nuclear plants or other electricity sources. Both U.S. and E.U. experts generally agreed that, given the various factors that might delay or block a nuclear plant, in 2010 a nuclear project would have to pay investors a higher rate—known as a risk premium—compared to, say, a comparable natural gas power project. Most experts expected this nuclear risk premium would decline by 2030, but not to zero, meaning that in addition to high capital costs, nuclear energy would also suffer from a higher financing rate for those costs. More information on the financing rate results is in the SI.

RD&D Recommendations and Impact on Costs and Non-Cost Factors. All but a few experts on both sides of the Atlantic recommended a large increase in government nuclear energy RD&D. For both E.U. and U.S. experts, the funding level recommended by the largest number of experts was 2.5−3 times the BAU level (see Figure S5 in the SI).

The participating experts generally agreed that their recommended increases in RD&D would have a relatively limited impact on future costs. Instead, expanded RD&D could result in improved performance in areas such as safety, waste management, and uranium resource utilization, and could lead to new capabilities such as provision of high-temperature process heat. Some reactor systems with desirable properties would simply not become available without additional public RD&D investment. Both sets of experts agreed that beyond roughly $3 billion a year in the U.S. or in the E.U., increases in nuclear RD&D investments would yield decreasing marginal returns.

Most experts indicated that increased public RD&D would not change the cost of Gen. III/III+ reactors. With respect to Gen. IV reactors, the participating E.U. experts projected that expanded RD&D would cut off the high tail of the projected cost distribution. Half of the U.S. experts share this view, while the second half is fairly pessimistic about the effect of expanding R&D effects on costs. Only a few experts in either group, however, projected that Gen. IV systems could reach costs below $3800/kW installed by 2030 even under their recommended RD&D funding. Similarly, all but a few experts thought that SMRs would cost $4000/kW or more in 2030, even under their recommended RD&D funding.

We also evaluated the relationship between the 50th percentiles of cost and the sector of the experts. Without controlling for any other factors, we found that industry experts were more pessimistic than experts in public institutions (on average their cost estimates were 458 $/kW greater, with a p-value of 0.06) and that academics were more optimistic than experts in public institutions (on average their cost estimates were 900 $/kW lower, with a p-value of 0.00).

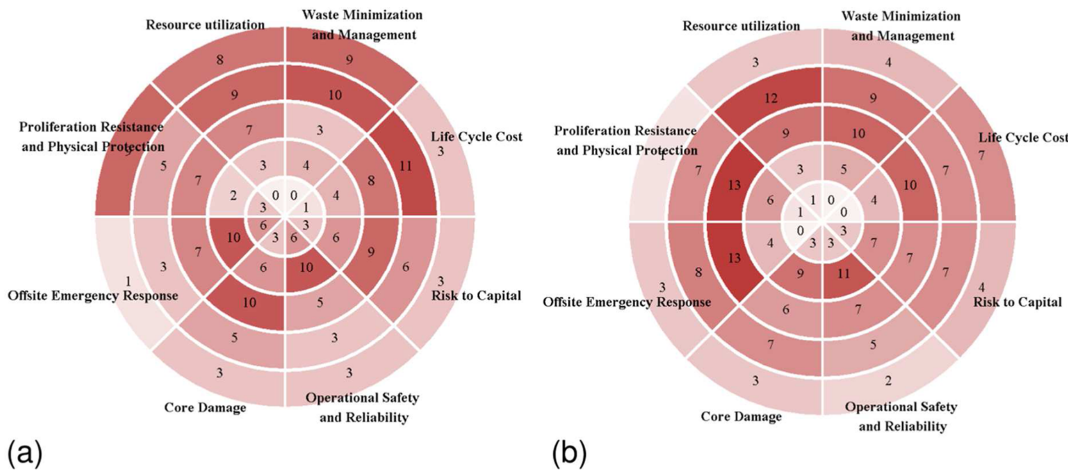

Figure 4. How much will RD&D programs under a BAU funding scenario contribute to addressing the different goals of RD&D programs (namely: resource utilization, waste minimization and management, lifecycle cost, risk to capital, operational safety and reliability, core damage, offsite emergency response, and proliferation resistance and physical protection) by 2030 according to U.S. (left, Figure 4a) and E.U. (right, Figure 4b) experts? The innermost ring = fully address; second ring = significantly address; third ring = moderately address; fourth ring = only partially address; outermost (fifth) ring = not address. The color is proportional to the number of experts in that category: a darker color means that many experts thought that BAU RD&D programs would have a particular level of impact in that particular goal. The graph refers to the Gen. IV reactor type that experts thought would be most commercially viable in 2030, which differs by expert.

Combining the answers of U.S. and E.U. experts regarding the 2030 costs under increasing RD&D scenarios, we are able to estimate the cost-reduction return from RD&D investments (see SI, section S7 for more details). With increasing public RD&D investments over the BAU RD&D level, the participating experts expect small cost reductions (particularly for already-designed large-scale Gen. III/III+ systems) and decreasing marginal returns per RD&D dollar spent. We use the concept of a returns to RD&D curve (on the analogy to the more commonly used learning curve based on cumulative capacity) drawing from the literature supporting the idea of decreasing returns to knowledge[33−37] to extract a relationship between RD&D investments under scenario i (RDi) and resulting 2030 overnight capital costs improvements over the BAU case. In particular, if $c(\mathrm{RD}_{\mathrm{BAU}})$ are costs under the BAU RD&D scenario, then the ratio of costs under scenario i to costs under BAU can be defined as follows:

$$\frac{c(\mathrm{RD}_i)}{c(\mathrm{RD}_{\mathrm{BAU}})} = \left(\frac{\mathrm{RD}_i}{\mathrm{RD}_{\mathrm{BAU}}}\right)^{\beta} \tag{1}$$

Where β is the returns to RD&D coefficient, implying that a doubling of RD&D would reduce costs by a fraction equal to $1-2^{\beta}$.

Table S2 in the SI shows that a best fit to the participating experts' projections implies that in the case of Gen. III/III+ reactors, each doubling of RD&D investments would lead to an additional cost reduction of only 1.36%. The corresponding figure for Gen. IV systems is 5.13%, implying a larger, though still modest, role for increased government RD&D in reducing 2030 costs. SMRs would benefit similarly from additional public RD&D, with a return to RD&D rate of 5.11%. The low values of the R^2 in the regression indicate that levels of RD&D investment are not the only factor affecting projections of future costs. An ANOVA analysis of the relationship between RD&D investments and the cost of the three reactor types indicated that including an "expert" variable increases the explanatory power of our specification, but does not affect the sign, value, or statistical significance of the RD&D component.

This concept of an exponential learning-by-researching curve with decreasing marginal returns is most appropriate for modeling incremental improvements in the costs of an established set of technologies. We would argue this is a good description of nuclear energy, where most of the current efforts are focused on improvements to reactor and fuel cycle concepts that originated decades ago. But in addition to incremental improvements, increasing RD&D also increases the probability of disruptive innovations that could lead to step-function shifts in cost or performance; these are more likely to occur in some other technological areas than they are in nuclear power at its current stage of development.

As noted above, RD&D has many other purposes that go well beyond reducing nuclear energy costs. The Gen. IV International Forum—the international consortium pursuing RD&D on the Gen. IV concepts—has defined a range of goals, and we asked the E.U. and U.S. experts to estimate how much each Gen. IV goal would be addressed by 2030 assuming BAU RD&D funding. The scale ranges over five steps: the inside step would indicate that the goal would be fully addressed (the inner ring of the pie chart in Figure 4); the outside step would indicate that the goal would not be addressed at all (the outer ring of the pie chart in Figure 4). We used a Likert-scale framing for these questions because they are preferable to yes/no questions[38] and and because it allowed us to keep a manageable survey length. To maximize the quality of the answers, we defined quantitatively what was meant by each of the five scales (see SI for passwords to the surveys to read the definitions). The numbers in each section of the rings are the count of experts who gave that rating for that goal; the shadings reflect this count.

Both U.S. and E.U. experts were optimistic that a BAU RD&D program would make major progress in addressing operational safety and reliability. Both groups are fairly pessimistic about a BAU program addressing waste minimization and management, resource utilization, or proliferation resistance and physical protection issues, though E.U. experts were less pessimistic than their U.S. counterparts (Figure 4). For both sets of experts, half of the ratings for life cycle costs

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are in the outer two rings (not addressed at all or only addressed in part).

Under their recommended budgets, 50% of the E.U. experts foresee that all objectives will be at least significantly addressed (the question in the U.S. survey is not comparable). It is noticeable that life-cycle cost and risk to capital are the only two goals that are almost insensitive to the increase in RD&D. Even though these improvements by 2030 seem modest, experts thought that these benefits justified large increases in RD&D because many Gen. IV designs are more likely to play a major role in the longer term (around 2050) and because of the important role that nuclear power could play in a world serious about reducing climate emissions. In the survey, the degree of progress was rated only as it affected likely future growth of nuclear energy; some experts may have believed that progress that would not greatly affect future growth but could reduce the risks of that growth would justify significant investment.

Recommended RD&D Allocations. What particular technological areas should an expanded nuclear RD&D investment focus on? On average, both U.S. and E.U. experts recommend devoting roughly a quarter of the investment to fuel cycle technologies and fuel materials, and agreement across experts on this point was relatively high (coefficients of variation between experts below 0.6) (Figure 5). Experts

(a)

EU experts	Specific reactor systems							Cross-cutting areas						Other
	GFR	SFR	LFR	SCWR	MSR	VHTR	SMR*	Fuel cycle	Fuels materials	Risk safety	Economics	Protection	Non-power	
Mean	6%	14%	5%	3%	2%	8%	7%	10%	12%	9%	5%	5%	7%	2%
Coefficient of variation	0.97	0.71	1.01	1.53	1.99	0.83	1.03	0.54	0.38	0.42	0.93	0.84	0.83	2.05

(b)

US experts	Specific reactor systems							Cross-cutting areas						Other
	GFR	SFR	LFR	SCWR	MSR	VHTR	SMR*	Fuel cycle	Fuels materials	Risk safety	Economics	Protection	Non-power	
Mean	3%	14%	3%	1%	3%	13%	11%	14%	11%	7%	4%	5%	5%	6%
Coefficient of variation	1.70	0.81	1.78	2.00	1.40	0.50	0.49	0.49	0.54	0.82	0.87	0.76	0.97	1.54

Figure 5. Average percentage budget allocation for E.U. (top, panel a) and U.S. (bottom, panel b) experts. The mean average allocation is color-coded from 0% to 15% (the redder the cell, the greater the average allocation). The coefficient of variation is color-coded from 0 to 2.1 (the darker the gray, the greater the disagreement across experts about the budget allocation for a particular RD&D area).

disagreed more over which particular reactor systems deserve expanded RD&D funding. Sodium-cooled fast reactors (SFR) attracted the largest average share of the experts' recommended budgets, both in the U.S. and the E.U. surveys, followed by the very high temperature reactor (VHTR).

SFRs, like most of the Gen. IV systems, are based on recycling spent fuel to extend uranium resources and, in some cases, improve waste management by transmuting long-lived isotopes. They have been under development since the 1950s at a cost of tens of billions of dollars in RD&D, but only a few countries expect to commercialize them before 2035.[39] Although the SFR and fuel cycle technologies received the highest average budget allocations, the rationale for focusing on fast reactors and recycling attracted the most polarized disagreement, with some experts arguing that uranium was cheap and abundant and any waste management improvements were not likely to be substantial, and others arguing that recycling could offer decisive waste management advantages, or that providing sufficient fuel to sustain large-scale growth of nuclear power over an extended period would require recycling.

The VHTR offers the potential to produce high-temperature process heat for chemical and industrial purposes; this would increase the reactors' overall efficiency and make it possible to produce electricity when electricity prices were high and other products at other times. E.U. experts on average allocated less to SMRs than their American counterparts, and in the workshop, most E.U. experts indicated that they did not envision any substantial market for smaller reactor systems.

Experts were also asked to provide the rationales for their top four funding allocations. For a summary of the top RD&D objectives identified by the experts as the main priorities for RD&D funding, the reader is referred to section S9 in the SI. Our analysis indicated that there was little correlation between experts' self-described areas of expertise and their RD&D funding allocations, suggesting little or no bias toward recommending RD&D that would benefit their own projects (see section S9 in the SI for additional discussion).

Sections S11 and S12 in the SI include a discussion of the results on the constraints on the future growth of nuclear power, and a discussion on the impact of the Fukushima accident on the estimates of the experts on the future growth of nuclear power, respectively. The experts who participated in the workshop made few changes in their funding allocations and only modest changes in their projections of nuclear power growth in response to the Fukushima accident.

DISCUSSION

Our expert elicitation revealed broad consensus among a wide range of industry, academic, and government laboratory experts in both the United States and the European Union that a large increase in government investment in nuclear energy RD&D is needed, but will lead to only modest improvements in nuclear energy costs. The primary benefits the experts envision are in other areas, such as improved safety and waste management or offering new capabilities such efficient spent fuel recycling or provision of high-temperature process heat. Different Gen. IV reactor designs offer possible benefits and trade-offs along different Gen. IV goals, which is why it may be too early to focus on a single reactor design (see SI, section S8).

Nuclear energy appears likely to continue on a path of slow to moderate growth after the Fukushima disaster, though some countries have turned away from this energy source. But our results raise serious questions about whether nuclear energy can achieve the dramatic growth required for it to play a significant part in mitigating climate change, dealing with limited supplies of liquid fossil fuels, or providing energy access to all. If the experts' cost projections prove to be correct, nuclear plants are not likely to be competitive with coal and natural gas plants in many major markets unless policies are put in place that have the effect of creating a substantial price on carbon. RD&D investments alone are not likely to be enough to achieve rapid nuclear energy growth. Such investments would have to be coupled with a range of government policies to support nuclear energy, and with widespread industry and public support.

Whether it will be possible to generate the broad support required in the aftermath of the Fukushima disaster remains to be seen.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information includes the following sections: (S1) the list of experts participating in the individual online elicitations and in the group discussion; (S2) logins to the E.U. and U.S. online elicitation tools; (S3) information on the design of the elicitation instrument; (S4) a brief analysis of cognitive and motivational biases; (S5) a discussion of insights obtained from the two-stage methodology of the elicitation; (S6) figures with experts estimates of the overnight capital costs of large-scale Gen. IV and SMR reactors in 2030; (S7) results on the returns to RD&D; (S8) a figure with the experts' recommended level of public investments in nuclear RD&D; (S9) a discussion of RD&D objectives; (S10) the experts estimates about the risk premium of nuclear power plants over those of natural gas plants at different points in time; (S11) expert judgments about nontechnical factors that may constrain the future of nuclear growth; and (S12) the results and a discussion of the impact of Fukushima on the expert estimates. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: (+1) 617-384-7325; fax: (+1) 617-495-8963; e-mail: laura_diaz_anadon@harvard.edu.

Notes

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