Supplementary Information:

Appendix S1. Other approaches to cost estimation

Analysts and policymakers must make important decisions in the face of uncertainty on how electricity-generating technologies are likely to evolve. Key factors include investment costs, operation and maintenance costs, technical performance, and public acceptability. Here, our focus is on assessing the future capital costs of integral light-water small modular nuclear reactors (SMRs). These constitute an emerging technology that uses the same operational principles as large light water reactors but in a size range of 300MW_e or less, as compared to conventional Gigawatt-scale units.

While they are not all applicable to projecting the future cost of SMRs, several methods deserve consideration: 1) running regression or econometric methods that use historical data to generate estimates; 2) employing scaling factors from technologies where costs are known and applying them to the new technology in question; 3) building component- and process-based bottom-up engineering-economic models; and 4) using structured expert interviews to elicit estimates.

One strategy is to investigate how similar technologies have performed in the past. There is ample literature on technological innovation related to electricity generating systems that uses regression and econometric models to estimate how the cost of these systems has evolved as their cumulative added capacity increases (this is termed “learning by doing”), as more research dollars are poured into their commercialization (“learning by researching”), or as a function of the implementation of policies that are designed to accelerate their market penetration. These investigations usually report their conclusions in terms of “learning rates”: the percentage reductions in the technologies’ costs when their installed capacity is doubled.

Although there have been several attempts to estimate nuclear power’s learning rates over the past few decades, the technology uniquely handicaps these efforts. The facts that (1) there are fewer than 450 nuclear power plants in the world and (2) the “technology” employed in these plants varies quite widely, meaning that many different plants sit on different cost curves, results in costs that are variable and generate little insight to guide estimates of future costs. We present a few reported learning rates here. In their 2001 study, McDonald and Schrattenholzer (S1) report learning rates for a number of energy technologies, including nuclear power plants. They estimate that the learning rate of nuclear power in the developed world (those countries that belong to the Organization for Economic Cooperation and Development) from 1975 to 1993 is about 6%; Using existing data on the American nuclear industry, as well as previously unpublished data on the French nuclear experience, Grubler (S2) finds an “observed real cost escalation [that] is quite robust against the data and model uncertainties that can be explored”. Grubler concludes that, for the Gigawatt-scale nuclear reactors in operation today, there is a “negative learning by doing” effect: specific costs increase rather than decrease with accumulated experience. He explains this by emphasizing several caveats associated with these data, including points made above. For example, Grubler notes the different institutional arrangements (such as safety regulations) that different reactors had to contend with, as well as the aforementioned cross-generational variations among nuclear reactor designs that make such comparisons questionable. Questioning recent claims of nuclear power's economic viability, Cooper (31) conducts a similar assessment of the costs of U.S. nuclear power plants. In his work, nuclear power exhibits an increasing cost trend as a function of the cumulative capacity installed.

These methods are inappropriate here because, in using learning rates to forecast future costs, a modeler implicitly assumes that the trend in future costs will be similar to what we have seen in the past. This does not hold for SMRs, the business case for which is predicated on the assumption that they will be factory-fabricated, unlike legacy nuclear plants. An even more fundamental point is that this strategy is indefensible for these SMRs, which are a new, emergent technology for which there is no historical data.

Another strategy is to estimate the cost of a new technology by applying a scaling factor to an existing benchmark. This could be done for SMRs by using the reported costs of large-scale nuclear reactors as a starting point, "scaling" the costs only by size (MW_e capacity). While Kuzentsov and Barkatullah acknowledge the fact that SMR cost estimates in 2009 may be mere conjecture, they explicitly adopt this approach (27). Another way of generating these estimates is by applying other theoretical scaling factors that take into account the inherent differences between the technologies. Because SMRs would be manufactured in a factory, for example, a researcher might scour the literature for an estimate of the cost reductions that factory fabrication generates in other industries, applying that factor (or a modified version of it) to the large reactor cost estimates he or she is using as a benchmark. Other factors that have been mentioned in the literature as being relevant for SMRs include technical progress economies and modular construction economies, among others. Carelli et al. (34) provide a good example of this approach.

A third method to estimate the future costs of SMRs is by using detailed component and process based bottom-up engineering-economic models. For example, the Electric Power Research Institute (EPRI) is working with vendors and utilities to develop an SMR utility requirements document (URD) that details the necessary components and processes for a given plant configuration (S3). Naturally, given the proprietary nature of design details and the complexity of this task, these estimates, especially if they are designed to be publically available, take time to develop. These efforts are valuable; they help modelers develop a better scope when generating estimates that include process and support facilities, fuel handling and storage equipment, and even the basic transmission yard infrastructure required for SMRs.

The final method, used in this paper, is a top-down expert elicitation, an approach to generating estimates that we explain in the methods section of our paper and in appendix S4 of the supplementary information. When well designed and executed, expert elicitation not only generates estimates, it provides a structured discussion that serves as an outlet for participating experts who are themselves uncertain of the future direction of their proposed technology. These discussions, while qualitative, generate much insight: they highlight questions experts think have yet to be addressed, for example, providing fertile ground for further assessment and public discourse. None of the other methods listed above do this.

In Figure S1, we compare our results with estimates of likely SMR cost from the literature derived using some of the methods outlined above. Notice the narrow range within which all of these prior estimates fall, when compared with the results of our elicitation. While our experts may be subject to overconfidence, these results suggest that other methods may be even more susceptible to underestimating costs and associated uncertainties. At this stage of such a complex technology's development, most of these prior estimates have either been derived using the "anchor" of large reactor costs or via consultation with a small number of experts. Notice also the lack of systematic treatment of uncertainty in many of these estimates.

Our experts also provided us with a wide range of estimates for large, current-generation nuclear reactors. There is a long history of cost estimates for conventional reactors that have turned out to be in serious error (S9). Figure S2 compares the estimated cost of nuclear plants prior to construction with their actual cost: in some cases, actual costs turned out to be many times greater than estimated cost (S10).

The fact that not all of the estimates we elicited for conventional reactors overlap indicates that, despite this history that all our experts know about, many are still producing cost estimates that are "overconfident" (i.e. too narrow). Despite our best efforts to reduce overconfidence during the elicitation, the same is probably also true for many, if not all, of the estimates for SMRs made by our experts. However, as Figure S1 suggests, the result we report are probably considerably less overconfident than previous estimates.

We are fully aware that, when it comes to an emergent technology like SMRs, there is much uncertainty on how costs and performance are likely to evolve over time. We do not argue that expert elicitation dominates other methods: instead we argue that given the uncertainty on how SMRs are likely to evolve in the near future, results from the different methods should be provided to decision-makers in order to inform them about the uncertainties regarding new technologies.

Appendix S1 References:

S1. McDonald A, Schrattenholzer L (2001) Learning rates for energy technologies. *Energy Policy* 29:255–261.

S2. Grubler A (2010) The cost of the French nuclear scale-up: A case of negative learning by doing. *Energy Policy* 38:5174–5188.

S3. Mulford TJ (2010) RIC 2010 Regulatory and Policy Issues for Small Modular Reactors (SMRs). *Presentation to the U.S. Nuclear Regulatory Commission*, Rockville, Maryland.

S4. Solan D et al. (2010) Economic and Employment Impacts of Small Modular Nuclear Reactors. *Energy Policy Institute*, *Boise State University*, Boise, ID.

S5. Welling C (2010) SMR Financing and Economics The Nuclear Option: Is Small Scale Nuclear Energy an Option for Alaska? *Presentation at the University of Alaska Fairbanks*, Fairbanks, AK.

S6. Nuclear Energy Agency (2011) Current Status, Technical Feasibility, and Economics of Small Nuclear Reactors. *Nuclear Energy Agency*, Paris, France.

S7. Cunningham N (2012) Small Modular Reactors: A Possible Path Forward for Nuclear Power. *American Security Project*, Washington, DC.

S8. Black G (2012) Estimating the Economic Impacts of Small Modular Reactors. *Presentation to the Platts 3rd Annual Small Modular Reactors Conference,* Arlington, VA.

S9. Ramana MV (2009) Nuclear Power: Economic, Safety, Health, and Environmental Issues of Near-Term Technologies. *Annu Rev Environ Resour* 34:127-152.

S10. Talabi S, Fischbeck P (2012) Advancing Risk Management in Nuclear Power Plant EPC Projects - An Empirical Evaluation of Risk Management Practices on Steam Generator Replacement Projects. *Proceedings of the 7th World Congress on Engineering Asset Management*, Springer, London, Deajeon, Korea Republic.

Figure Legends:

Figure S1: A comparison of our elicitation results with existing estimates of SMR cost, the sources of which are listed either in the main manuscript or in appendix S1. Estimates were adjusted for inflation and, like our results, are presented in 2012 dollars.

Figure S2: Nuclear power has a record of poor and optimistic cost estimation. As this plot by Talabi and Fischbeck (S10) shows, in some cases, actual costs turned out to be many times greater than the cost estimates made prior to construction.

Figure S1

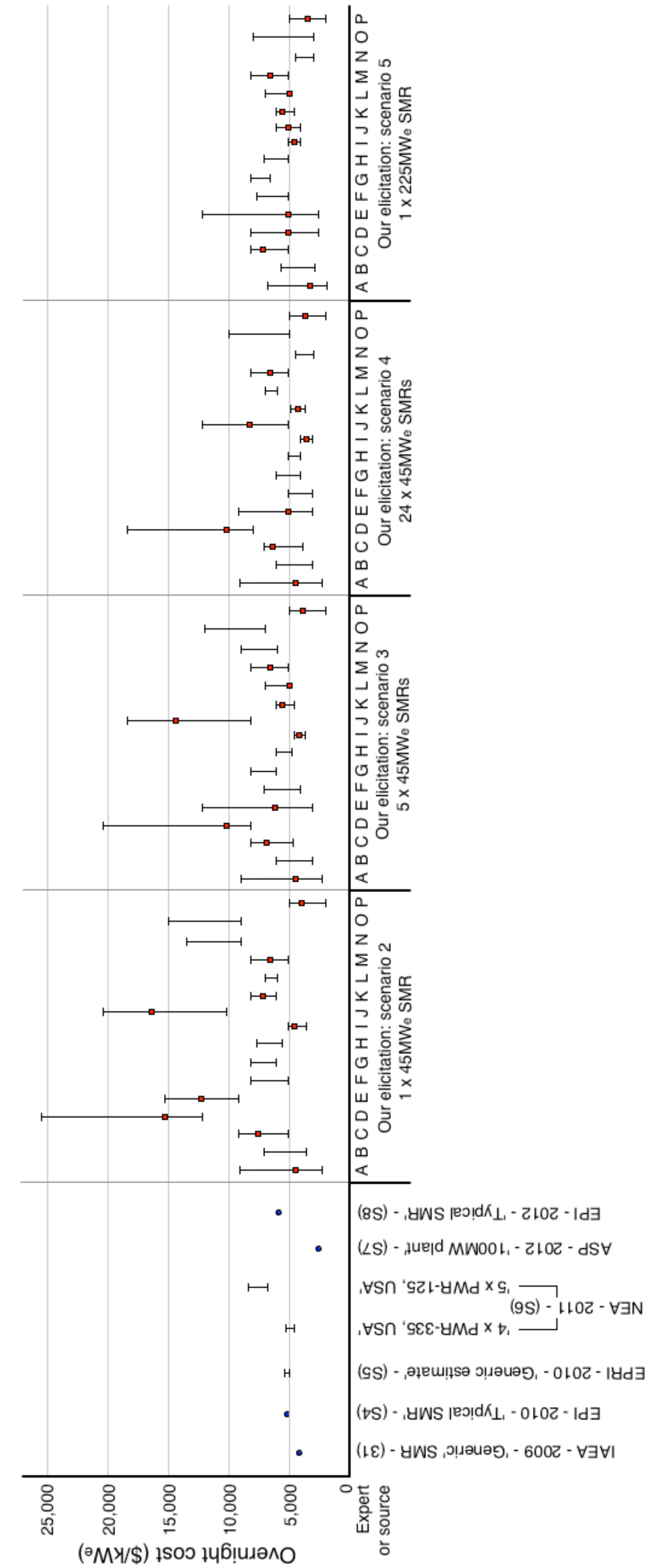
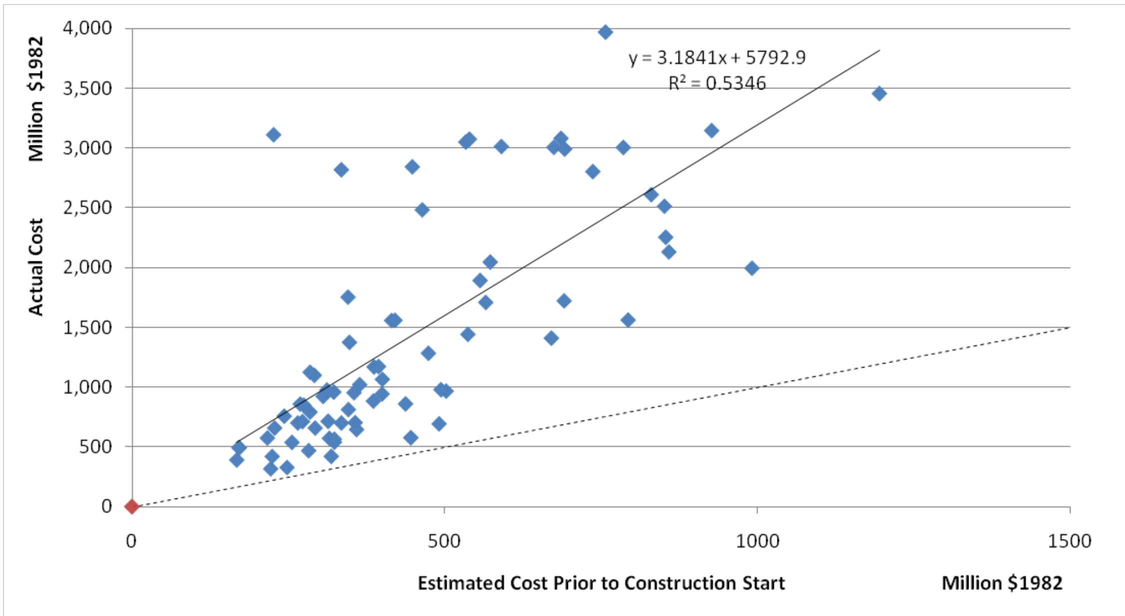

Overnight cost ($/kWe)
25,000
20,000
15,000
10,000
5,000
0
Expert or source
IAEA - 2009 - 'Generic' SMR - (31)
EPI - 2010 - 'Typical SMR' - (S4)
EPRI - 2010 - 'Generic estimate' - (S5)
'4 x PWR-335, USA'
NEA - 2011 - (S6)
'5 x PWR-125, USA'
ASP - 2012 - '100MW plant' - (S7)
EPI - 2012 - 'Typical SMR' - (S8)
A B C D E F G H I J K L M N O P
Our elicitation: scenario 2
1 x 45MWe SMR
Our elicitation: scenario 3
5 x 45MWe SMRs
Our elicitation: scenario 4
24 x 45MWe SMRs
Our elicitation: scenario 5
1 x 225MWe SMR

Figure S2


y = 3.1841x + 5792.9
R² = 0.5346
Actual Cost Million $1982
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
0
0
500
1000
1500
Estimated Cost Prior to Construction Start
Million $1982

Supplementary Information:

Table S1: A list of small (<300MW$_e$) reactor designs, sorted alphabetically by country, then by name. The reactor types are as follows: iPWR = integral pressurized water reactor; PWR = pressurized water reactor; BWR = boiling water reactor; HWR = heavy water reactor; LMR = liquid metal reactor; HTR = high temperature gas cooled reactor; MSR = molten salt reactor; and TWR = traveling wave reactor.

No.	Name	Developer	Country	Reactor type	Capacity (MW$_e$)	Ref.
1	CAREM-25	CNEA	Argentina	iPWR	25-150	26
2	FBNR	FURGS	Brazil	iPWR	72	26
3	ACP100	CNNC	China	PWR	100	S11
4	CEFR	CNEIC	China	LMR	20	26
5	CNP-300	CNNC	China	PWR	325	26
6	HTR-PM	Tsinghua University	China	HTR	105	26
7	Flexblue	DCNS	France	PWR	50 - 250	26
8	PHWR-220	NPCIL	India	HWR	235	26
9	4S	Toshiba	Japan	LMR	10	26
10	SMART	KAERI	Korea	iPWR	100	26
11	ABV-6M	OKBM	Russia	PWR	8.6	26
12	BREST-OD-300	RDIPE	Russia	LMR	300	26
13	KLT-40S	OKBM	Russia	PWR	35	26
14	RITM	OKBM	Russia	iPWR	50	26
15	SVBR-100	JSC AKME	Russia	LMR	100	26
16	UNITHERM	RDIPE	Russia	PWR	2.5	26
17	VK-300	RDIPE	Russia	BWR	250	26
18	WWER-300	OKBM	Russia	PWR	300	26
19	EM^2	General Atomics	USA	HTR	240	26
20	G4M	Gen 4 Energy	USA	LMR	25	26
21	SMR-160 (HI-SMUR)	Holtec International	USA	PWR	160	*
22	mPower	Babcock & Wilcox	USA	iPWR	180	26
23	NuScale	NuScale Power	USA	iPWR	45	26
24	PRISM	GEH	USA	LMR	155	26
25	Traveling Wave Reactor	Terrapower	USA	TWR	~300	S12
26	Westinghouse SMR	Westinghouse	USA	iPWR	225	26

*Anton S. SMR-160: An Unconditionally Safe Source of Pollution-Free Nuclear Energy for the Post-Fukushima Age. Presentation to the Nuclear Energy Standards Coordination Collaborative, July 17, 2012, Washington, DC.

Table S1 References:

S11. Sun S, Zhang L (2011) The Development of Multi-Purpose Modular Reactors with Improved Safety in China. *Presentation to the INPRO Dialogue Forum on Nuclear Energy Innovations, International Atomic Energy Agency*, Vienna, Austria.

S12. Ellis T et al. (2010) Traveling-Wave Reactors: A Truly Sustainable and Full-Scale Resource for Global Energy Needs. *Proceedings of ICAPP '10*, San Diego, CA.

Supplementary Information:

Appendix S2. Full expert elicitation protocol

Elicitation of Expert Assessments of Small Modular Reactor Costs

Interview Protocol

Expert: ______________________________

Date: ______________________________

Ahmed Abdulla
Graduate Student
Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, PA 15213

aya1@cmu.edu
412 – 953 – 3425 (mobile)
http://cedm.epp.cmu.edu

Inês Azevedo
Assistant Research Professor
Engineering and Public Policy
Director, Climate and Energy
Decision Making (CEDM) Center
Carnegie Mellon University
Pittsburgh, PA 15213

iazevedo@cmu.edu
412 – 268 – 5847 (office)
http://cedm.epp.cmu.edu

M. Granger Morgan
Lord Chair Professor of
Engineering
Department Head,
Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, PA 15213

gm5d@andrew.cmu.edu
412 – 268 – 2672 (office)
http://www.epp.cmu.edu

Outline of the Interview Protocol

Part I.	Introduction
Part II.	How will this elicitation work? A note on the pitfalls of elicitation.
Part III.	Demographic information
Part IV.	Background information on technologies under consideration
Part V.	Eliciting overnight costs
Part VI.	Plant modules under consideration
Part VII.	Eliciting construction schedules
Part VIII.	What is the influence of modularity on costs?
Part IX.	What is the perfect SMR deployment scenario?
Part X.	Which SMR-specific characteristics make them particularly economically attractive?
Part XI.	Which safety and security concerns pose the greatest challenges to SMR development, deployment, and operation?
Part XII.	Open-ended questions

Part I. Introduction

Because SMRs have yet to be constructed, there is no data that would allow for a bottom-up analysis of economic costs to take place. All current cost estimates use large reactor (LR) costs as a proxy when discussing the economics of SMRs.

We are working to elicit costs for the construction of small, modular nuclear reactors (SMRs) of the light water variety. Our goal is to assess when an economic case can be made for SMRs.

Thank you for your participation!

Will reference be made to proprietary blueprints?
No. Generic, publicly available blueprints of SMRs will be used in the elicitation. Investigators will not ask for proprietary information regarding a particular SMR design.

Will hard data be elicited for a particular SMR design?
No. We will not ask for design-specific hard data that might compromise proprietary vendor information.

What will you receive upon the completion of the procedure?
We will deliver a report assessing SMR economic viability using the elicited estimates. If respondents' anonymity can be protected, we will deliver individual, anonymized estimates from each expert also.

How will participants' anonymity be protected?
Each participant will be assigned a number. No names will be recorded. We will use this number both on the audio tapes and on the transcribed results. Audio tapes will be destroyed once the transcription process is completed.

Part II. How will this elicitation work?

On the following pages, you will be asked questions relating to the economic viability of two light water SMR designs.

The procedure will first entail the collection of some demographic information about you – the expert – in a form that doesn't directly identify you.

We have divided the International Atomic Energy Agency's (IAEA's) code of accounts for a conventional nuclear power plant into twelve capital cost modules. We will briefly discuss how each of these modules will be influenced by the move from conventional – i.e. skeletal – construction to SMR plants.

Estimates for the capital cost of SMRs – and for some SMR components – will then be elicited. We will first elicit the lower-bound estimate (in your judgment, what is the lowest possible cost for said component), then the upper-bound estimate, before asking for an estimate of 'most likely' cost, which would be your 'best guess'. We do this to avoid some of the more prominent pitfalls of expert elicitation, as discussed in the adjacent panel to the right.

We are also trying to determine which factors specific to SMRs make them most economically viable in your opinion. Similarly, what safety concerns are most likely to impede SMR deployment?

In each of these sections, we hope to engage in a substantive discussion. If you are not comfortable with a question, do not hesitate to outline your grievances. **If you wish to interject with a note you believe is of particular importance, we urge you to do so.** This elicitation procedure will be recorded only for the purposes of transcribing your responses. Upon completion of this transcription, all tapes will be destroyed.

A note on the pitfalls of elicitation

The academic literature is replete with evidence emphasizing the subjective nature of elicitation procedures such as these. There remains no clear-cut formula for how to robustly assess and adjust for this subjectivity.

Research shows that respondents – both experts and laypeople – have a tendency to be **overconfident** when answering questions. The cognitive heuristics that plague elicitation procedures include the *availability* and the *anchoring and adjustment* heuristics. In the ***availability* heuristic**, a respondent's answer depends on how easy it is to recall answers to previously-asked, similar questions. In the ***anchoring the adjustment* heuristic**, a respondent chooses an answer that then becomes an anchor. All discussions revolve around this natural starting point. This anchor, insufficiently adjusted, biases the final result.

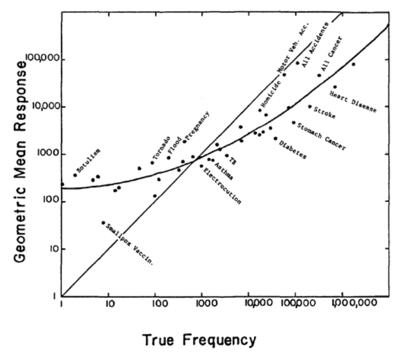
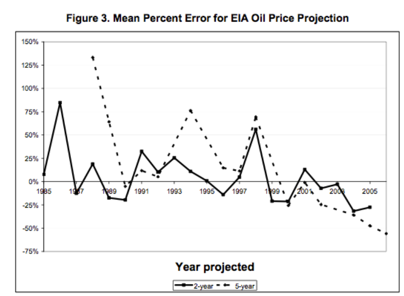


Figure demonstrating the availability heuristic. From Lichtenstein et al. (1978)



Anchoring & adjustment in EIA forecasts. From Fischer et al. (RFF 2008)

For information on these heuristics, and on dealing with uncertainty in quantitative risk and policy analysis, please consult *Uncertainty*, by Morgan and Henrion.

Part III. Demographic information

We will now collect some basic demographic information. This information should have little bearing on our final results. We only wish to collect this information in order to highlight more accurately the sum of skills and experience we have managed to incorporate into our investigation.

Year you first worked in the nuclear industry: ____________________

Number of years spent in the nuclear industry: ____________________

Number of years spent in management (if any): ____________________

Highest level of educational attainment: ____________________

Age: ____________________

In which of the following areas do you have professional experience? Please check all that apply:

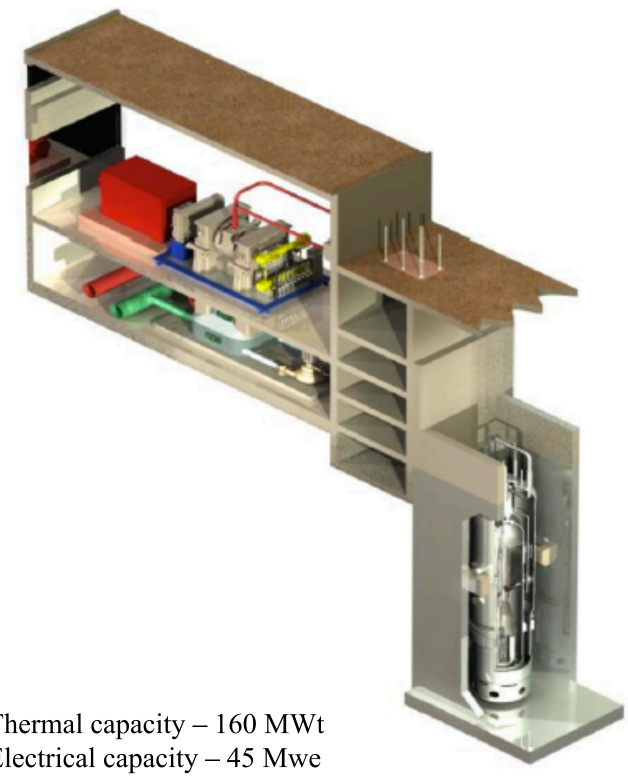
- [ ] Auditing / Financial / Accounting
- [ ] Government relations / Marketing / PR
- [ ] Human resources / Legal
- [ ] Technical services / Operations / Research and Development
- [ ] Management / Project Management
- [ ] Supply chain logistics

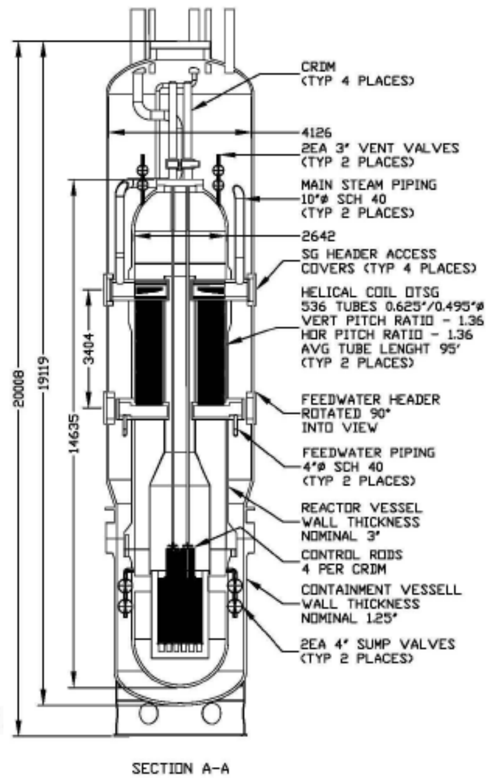
In which category does your current position fall?

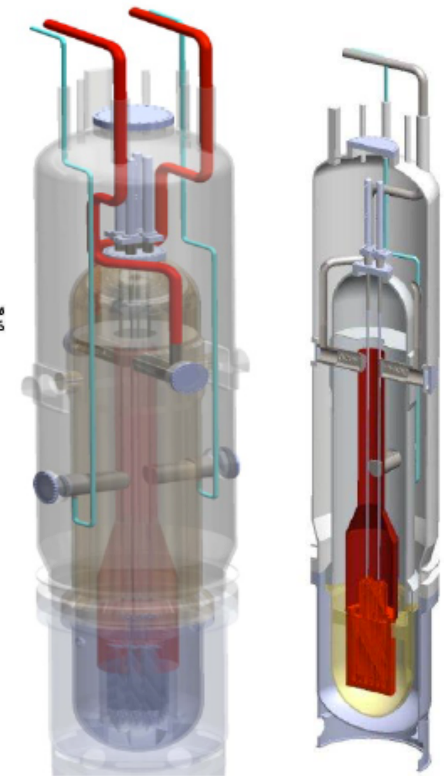
- [ ] Auditing / Financial / Accounting
- [ ] Government relations / Marketing / PR
- [ ] Human resources / Legal
- [ ] Technical services / Operations / Research and Development
- [ ] Management / Project Management
- [ ] Supply chain logistics

Part IV. Background information on SMR number 1

We will consider two SMR technologies in this elicitation. Publicly-available images and statistics are presented here:





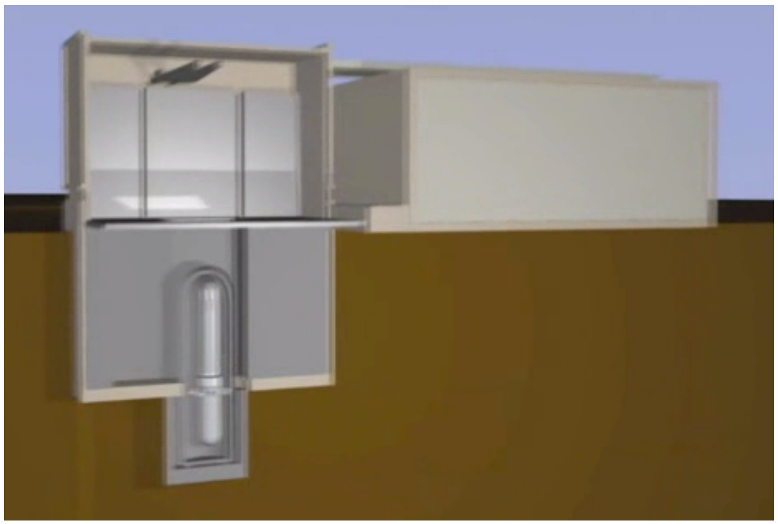


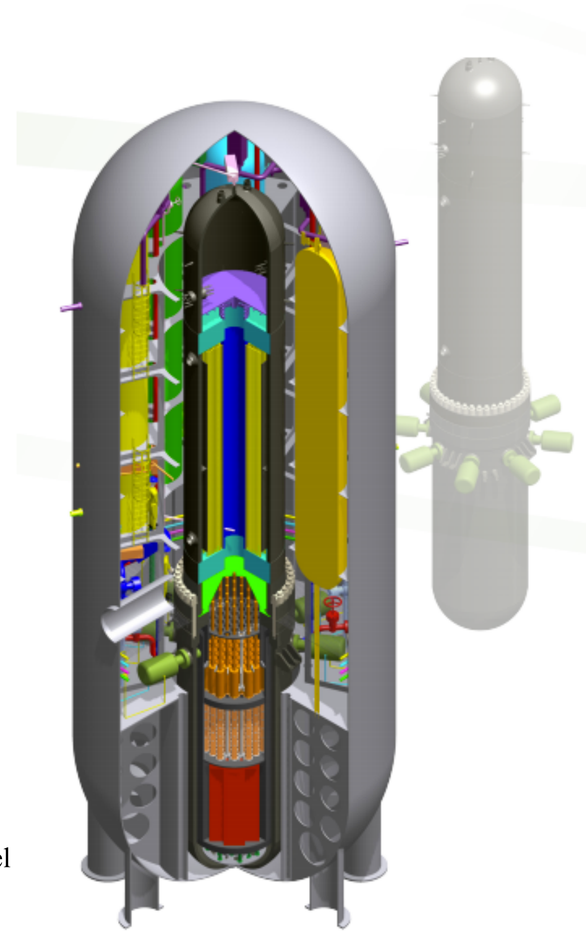
Thermal capacity – 160 MWt
Electrical capacity – 45 Mwe
Capacity factor – greater than 90 percent
Containment dimensions – 60 ft. by 14 ft. (diameter) containment vessel module
RPV dimensions – 45 ft. by 9 ft. (diameter) reactor vessel module
RPV weight – 300 tons as shipped from fabrication
Fuel – standard LWR fuel in 17 x 17 configuration. 24 assemblies. Each 6 ft. long.

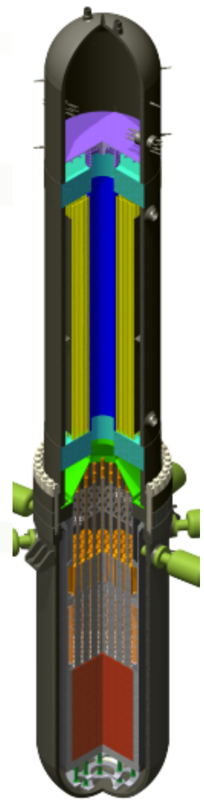
We shall call this design SMR Number 1

The picture to the left is taken from CleanTechnica (http://c1.cleantechnica.com/files/2008/07/nuscale_power_module.jpg). The pictures in the center and to the right are taken from Dr. Jose Reyes' (NuScale CTO) "Introduction to NuScale Design" pre-application presentation to the Nuclear Regulatory Commission (July 24, 2008).

Part IV. Background information on SMR number 2





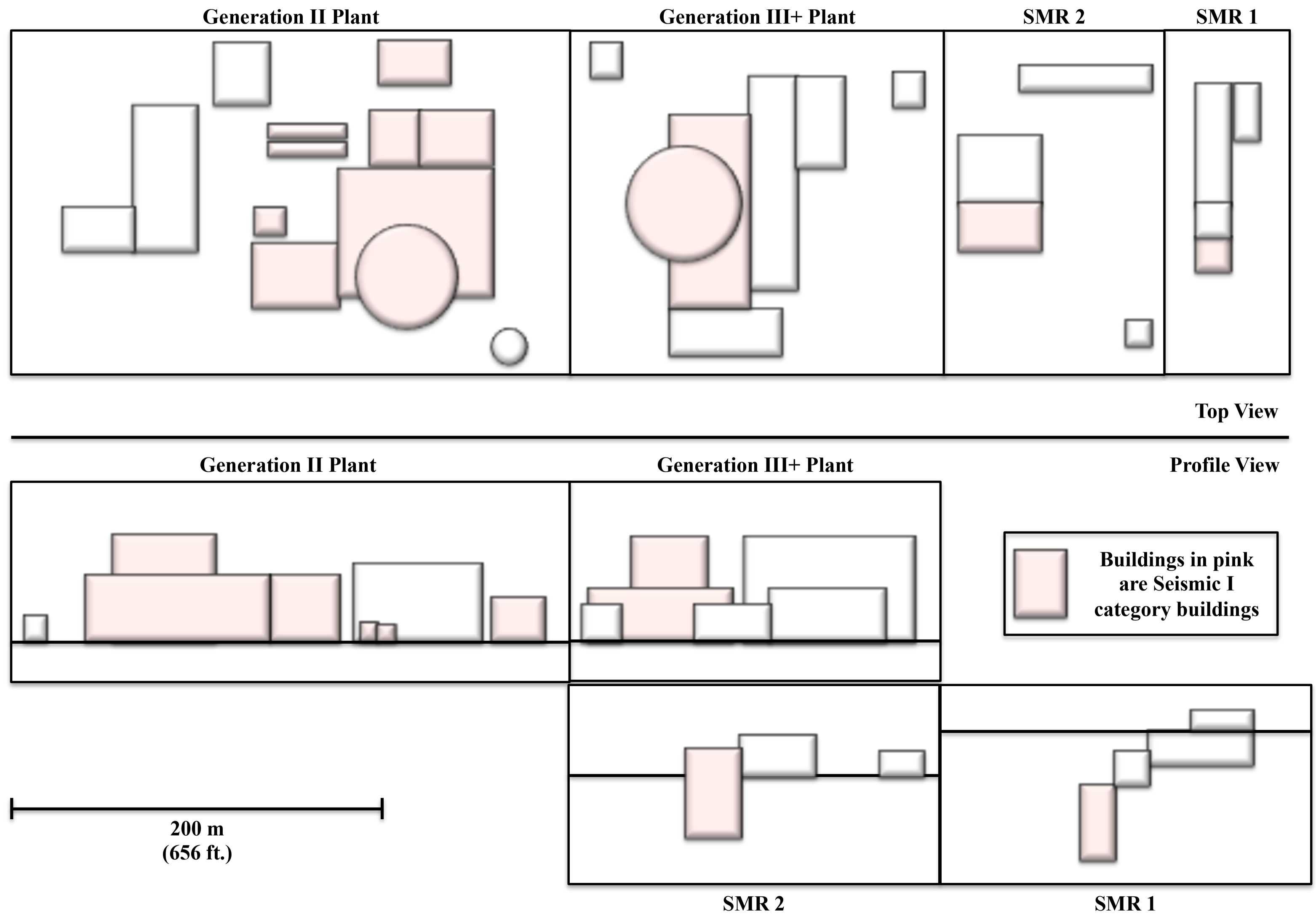


Thermal capacity – 800 MWt
Electrical capacity – 225 Mwe
Capacity factor – greater than 90 percent
Containment dimensions – 89 ft. by 32 ft. (diameter) containment vessel
RPV dimensions – 81 ft. by 12 ft. (diameter) reactor vessel module
RPV weight – unknown
Fuel – standard LWR fuel in 17 x 17 configuration. 89 assemblies. Each 8 ft. long.

We shall call this design SMR Number 2

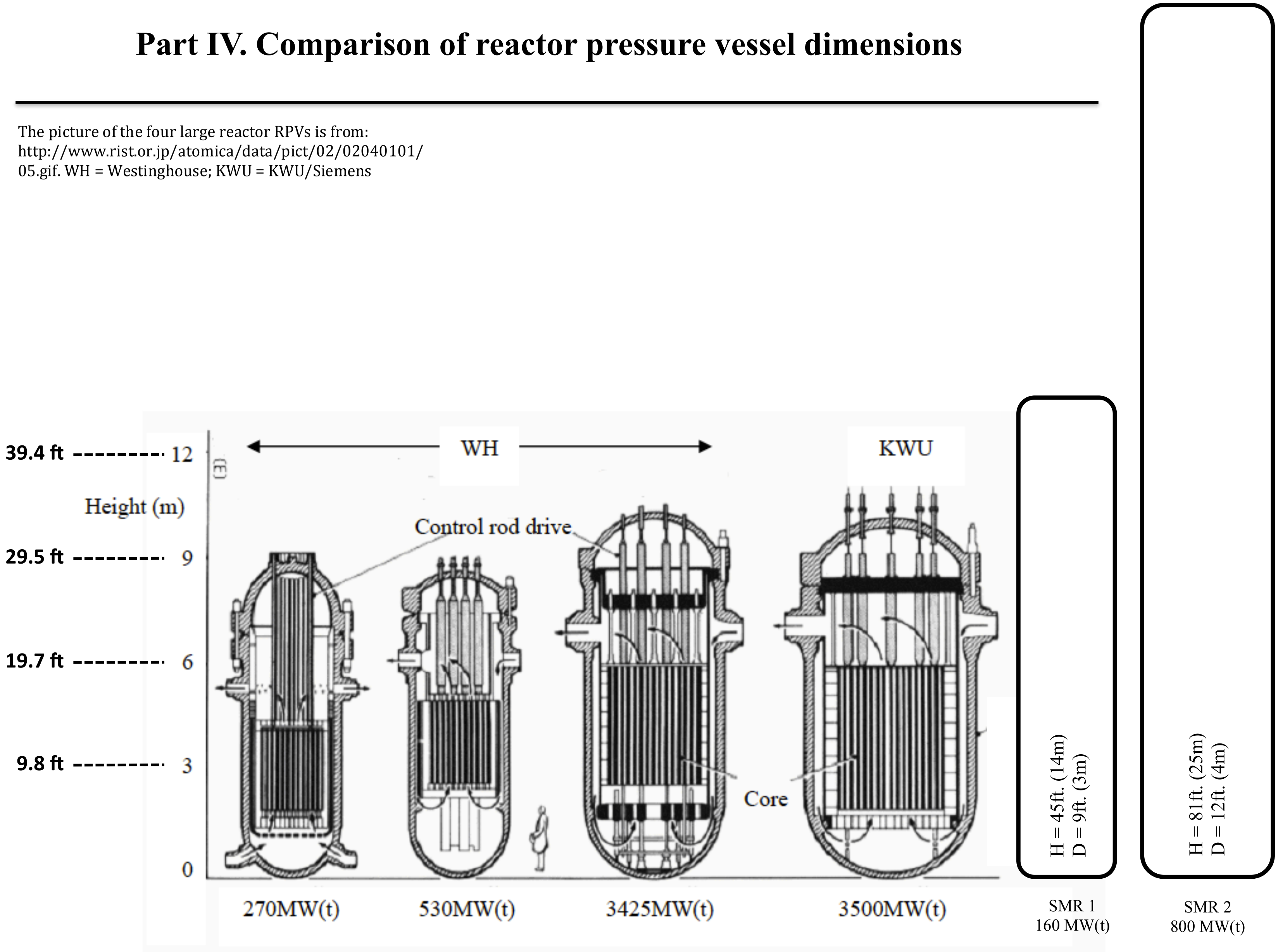
The picture to the left is a snapshot taken from the Westinghouse SMR video (http://www.westinghousenuclear.com/smr/smr.wmv). The picture in the center is a snapshot taken from the Westinghouse website (http://www.westinghousenuclear.com/smr/smr.swf). The picture to the right is taken from the Westinghouse SMR product sheet (http://www.westinghousenuclear.com/smr/fact_sheet.pdf).

Part IV. Hypothetical nuclear power plant footprints



Part IV. Comparison of reactor pressure vessel dimensions

The picture of the four large reactor RPVs is from: http://www.rist.or.jp/atomica/data/pict/02/02040101/05.gif. WH = Westinghouse; KWU = KWU/Siemens

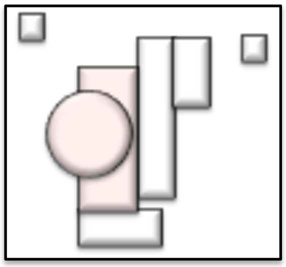


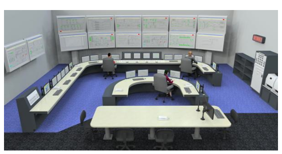
Part IV. We would like to explore the 5 scenarios below

Scenario 1

Plant with 1 GenIII+ conventional reactor

1,000 MWe



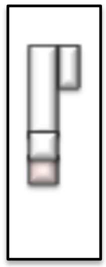


Buildings in pink are Seismic I category buildings

Scenario 2

Plant with 1 x SMR 1

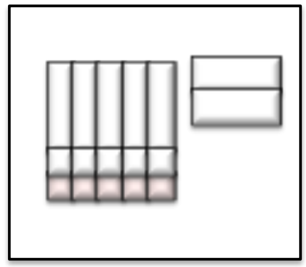
45 MWe



Scenario 3

Plant with 5 x SMR 1

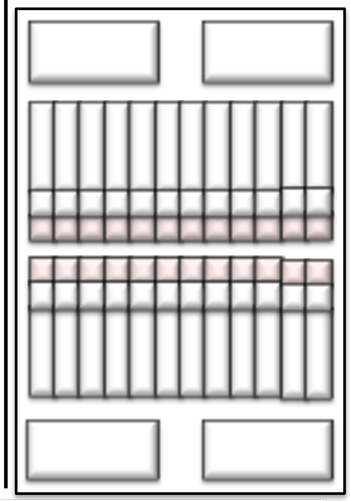
225 MWe

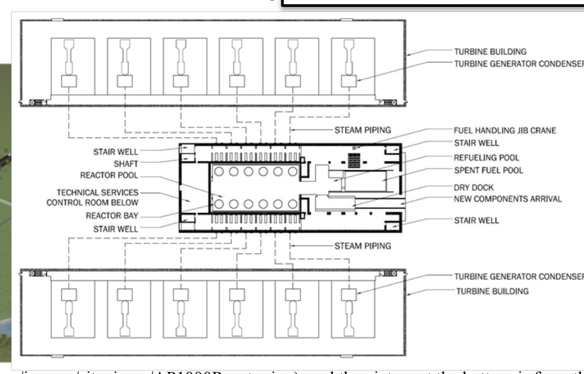


Scenario 4

Plant with 24 x SMR 1

1,080 MWe

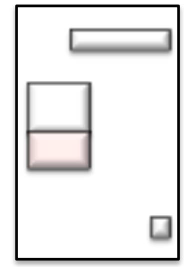


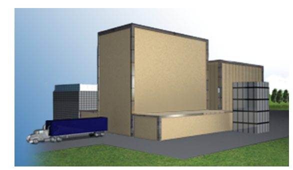


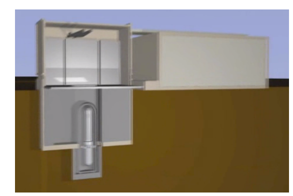
Scenario 5

Plant with 1 x SMR 2

225 MWe







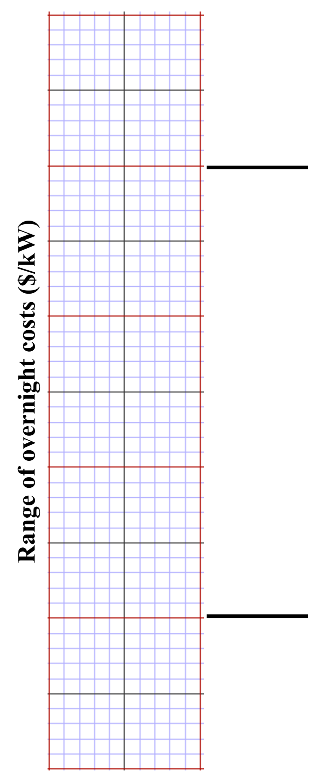
Scenario 1: the picture at the top is from the Institute for Southern Studies (http://www.southernstudies.org/images/sitepieces/AP1000Reactor.jpg), and the picture at the bottom is from the IAEA (http://aris.iaea.org/sonar/image/p00179_image016.jpg). Scenarios 2 through 4: the pictures are from the the IAEA, clockwise from top (control room: http://aris.iaea.org/sonar/image/NuScale/NuScale%20-%20Fig%208%20-%20Control%20Room.png, twelve-unit plant blueprint: http://aris.iaea.org/sonar/image/NuScale/NuScale%20-%20Fig%209%20-%2012%20unit%20model.png, and twelve-unit plant layout: http://aris.iaea.org/sonar/image/NuScale/NuScale%20-%20Fig%2010%20-%2012%20unit%20layout.png). Scenario 5: the picture at the top is from the Westinghouse website (http://www.westinghousenuclear.com/smr/images/smr_main_header.png) and the picture at the bottom is a snapshot taken from the Westinghouse SMR video (http://www.westinghousenuclear.com/smr/smr.wmv).

Part V. Eliciting overnight costs – demonstration

In your best engineering judgment, given the information currently available and your experience in the industry, what range of overnight costs – in dollars per kW – do you expect in each of the following scenarios? Below, we demonstrate the format in which we would like the answer to this question.

Scenario 0

Demonstration



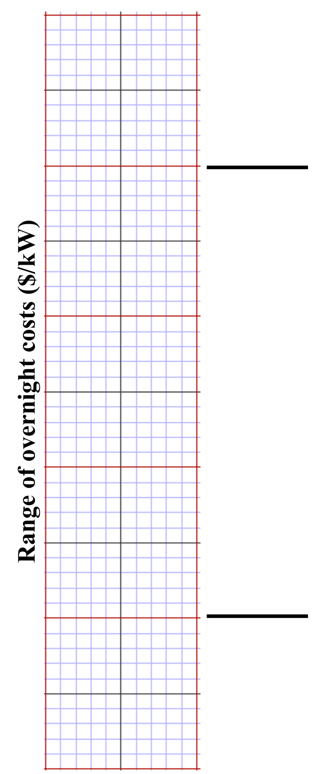
Part V. Eliciting overnight costs – conventional reactor plant

In your best engineering judgment, given the information currently available and your experience in the industry, what range of overnight costs – in dollars per kW – do you expect for a conventional, 1,000 MWe nuclear power plant?

Scenario 1

Plant with 1 GenIII+ conventional reactor

1,000 MWe



Part V. Eliciting overnight costs – SMR plant scenarios

In your best engineering judgment, given the information currently available and your experience in the industry, what range of overnight costs – in dollars per kW – do you expect for each of the SMR plant scenarios below?
We assume that the SMR plants are populated with Nth-of-a-kind SMR modules.

Scenario 2	Scenario 3	Scenario 4	Scenario 5
Plant with 1 x SMR 1	Plant with 5 x SMR 1	Plant with 24 x SMR 1	Plant with 1 x SMR 2
45 MWe	225 MWe	1,080 MWe	225 MWe
Range of overnight costs ($/kW)	Range of overnight costs ($/kW)	Range of overnight costs ($/kW)	Range of overnight costs ($/kW)

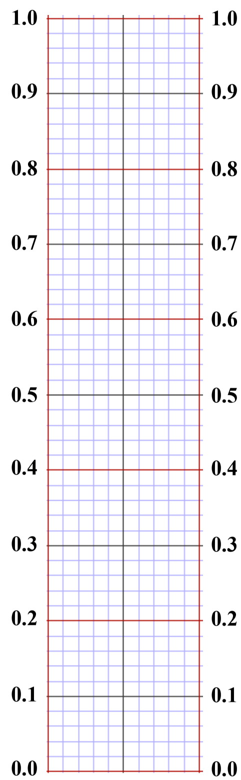
Part V. Probability of scenarios achieving a target cost - 1

What is the probability of each scenario achieving an overnight cost
less than $4,000 per kW when it achieves Nth-of-a-kind penetration?

Scenario 1

Plant with 1 GenIII+ conventional reactor

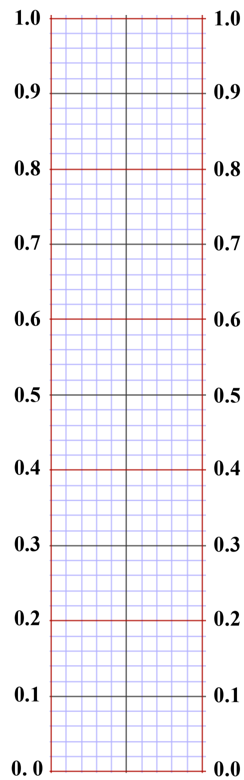
1,000 MWe



Scenario 2

Plant with 1 x SMR 1

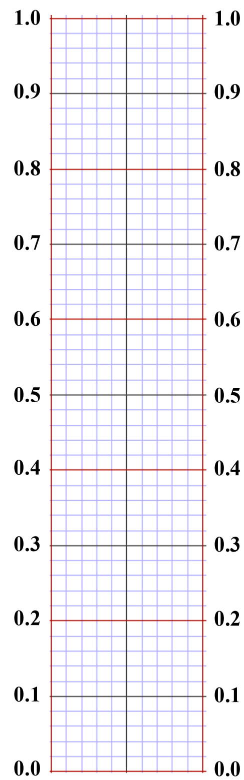
45 MWe



Scenario 3

Plant with 5 x SMR 1

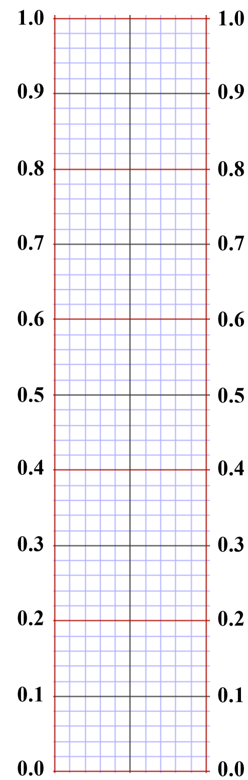
225 MWe



Scenario 4

Plant with 24 x SMR 1

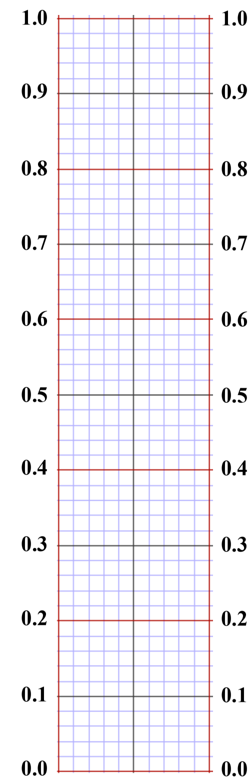
1,080 MWe



Scenario 5

Plant with 1 x SMR 2

225 MWe



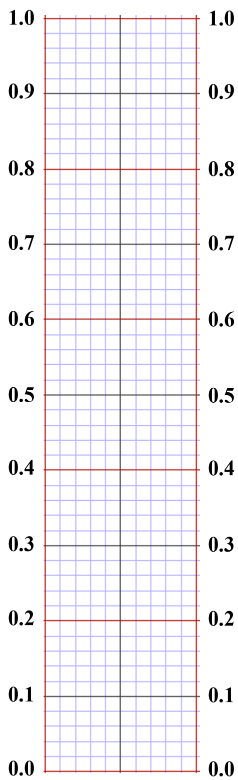
Part V. Probability of scenarios achieving a target cost - 2

What is the probability of each scenario achieving an overnight cost greater than $6,000 per kW when it achieves Nth-of-a-kind penetration?

Scenario 1

Plant with 1 GenIII+ conventional reactor

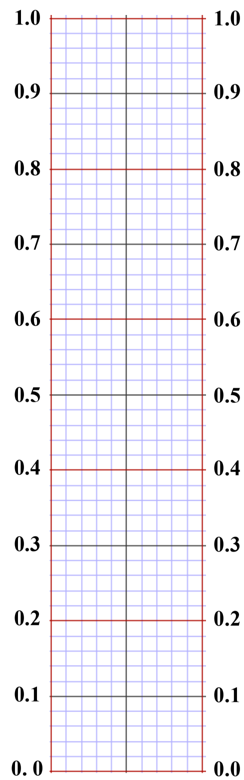
1,000 MWe



Scenario 2

Plant with 1 x SMR 1

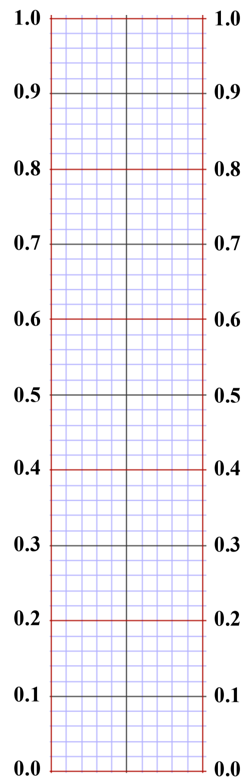
45 MWe



Scenario 3

Plant with 5 x SMR 1

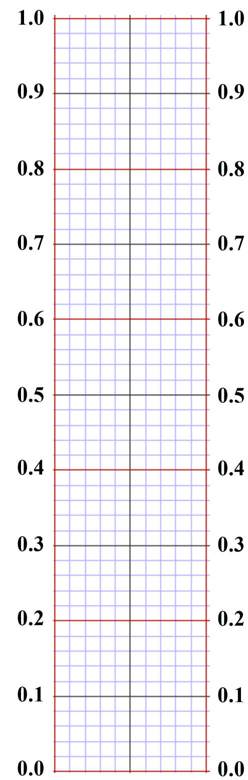
225 MWe



Scenario 4

Plant with 24 x SMR 1

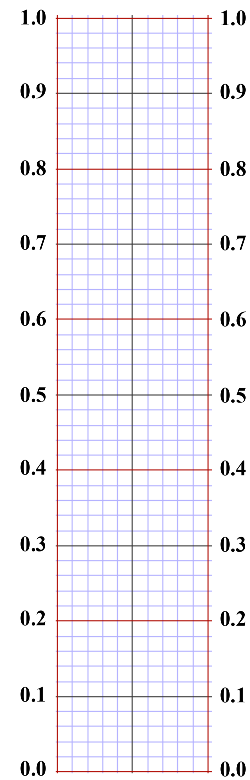
1,080 MWe



Scenario 5

Plant with 1 x SMR 2

225 MWe



Part VI. Ranking conventional plant modules under consideration

Using the IAEA Code of Accounts (2000), we have condensed the capital investment in a power plant into twelve modules. These are shown below. Please rank the modules based on the share of capital cost that each accounts for *(rank of 1 for the module that accounts for the greatest share)*. We are referring to the capital costs associated with construction of a conventional 1,000 MWe nuclear power plant.

We divide a nuclear power plant into the following modules:	*Rank*	
Building and site preparation	☐	______
Reactor plant equipment	☐	______
Turbine plant equipment	☐	______
Generator plant equipment	☐	______
Condensate, feedwater, and main steam system	☐	______
Water intake and water rejection	☐	______
Electrical equipment and I&C plant equipment	☐	______
HVAC and fire fighting equipment	☐	______
Site equipment (cranes, hoists, elevators)	☐	______
Engineering, design, and layout services	☐	______
Construction labor, project management, facilities, and tools	☐	______
Transportation and transportation insurance	☐	______

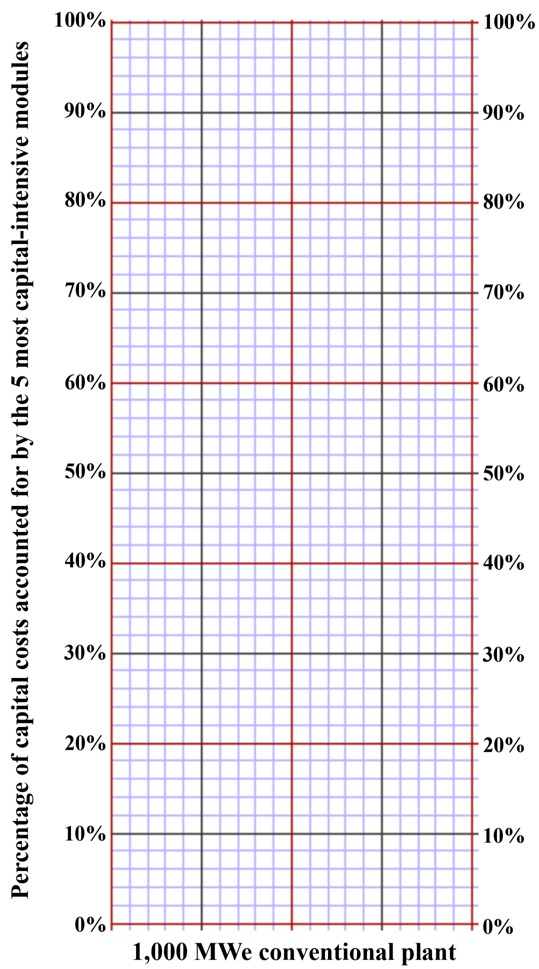
Part VI. Ranking SMR plant modules under consideration

We now want you to think about SMRs in general. Given the inherent characteristics of SMR plants, please rank once more the modules based on the share of capital cost that – in your engineering judgment – each will account for (rank of 1 for the module that accounts for the greatest share).

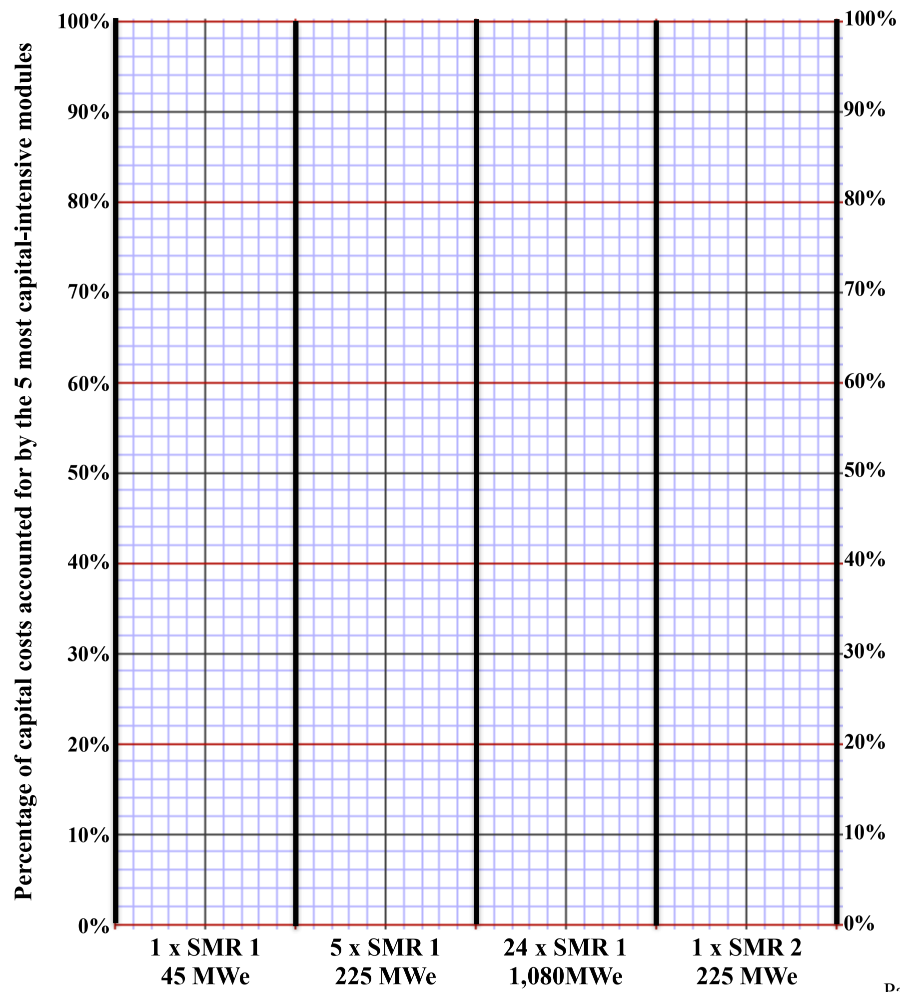
We divide a nuclear power plant into the following modules:	*Rank*	*Do you foresee any of the modules being irrelevant for SMRs? Would you suggest we ignore some of the modules listed?*
Building and site preparation	☐	☐
Reactor plant equipment	☐	☐
Turbine plant equipment	☐	☐
Generator plant equipment	☐	☐
Condensate, feedwater, and main steam system	☐	☐
Water intake and water rejection	☐	☐
Electrical equipment and I&C plant equipment	☐	☐
HVAC and fire fighting equipment	☐	☐
Site equipment (cranes, hoists, elevators)	☐	☐
Engineering, design, and layout services	☐	☐
Construction labor, project management, facilities, and tools	☐	☐
Transportation and transportation insurance	☐	☐

Part VI. Percentage of costs accounted for by 5 top-ranked plant modules

For a typical 1,000 MWe conventional plant:
What percentage of capital costs do you foresee the top five modules you chose on page 15 will account for?



For SMR plants:
What percentage of capital costs do you foresee the top five modules you chose on page 16 will account for?



Part VI. In top-down analyses, can modules be scaled using conventional reactor costs?

In the literature, authors scale gross capital costs by reactor capacity. We would now like to explore this approach to determining SMR plant capital costs. For a first attempt at a top-down cost estimate, is it fair to assume that some of the costs associated with a plant operating SMRs are scalable relative to the base case of a conventional (1,000 MWe) nuclear power plant?

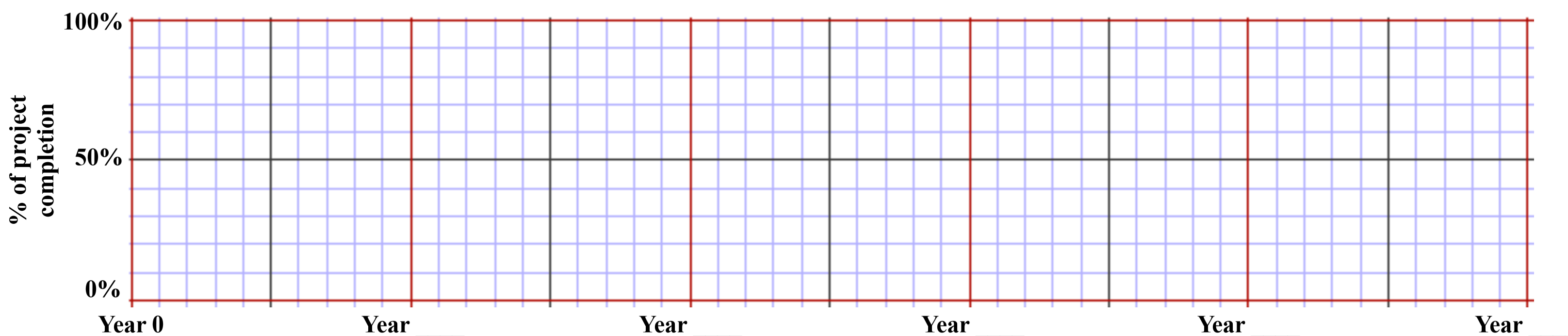
In your engineering judgment, is it appropriate to scale SMR plant capital costs? For each of the modules below, please check the appropriate boxes and note caveats, if any.

	Not scalable	*Scalable by reactor capacity*	*Scalable by plant footprint*	*Scalable, but with caveats*	
Building and site preparation	☐	☐	☐	☐	______
Reactor plant equipment	☐	☐	☐	☐	______
Turbine plant equipment	☐	☐	☐	☐	______
Generator plant equipment	☐	☐	☐	☐	______
Condensate, feedwater, and main steam system	☐	☐	☐	☐	______
Water intake and water rejection	☐	☐	☐	☐	______
Electrical equipment and I&C plant equipment	☐	☐	☐	☐	______
HVAC and fire fighting equipment	☐	☐	☐	☐	______
Site equipment (cranes, hoists, elevators)	☐	☐	☐	☐	______
Engineering, design, and layout services	☐	☐	☐	☐	______
Construction labor, project management, facilities, and tools	☐	☐	☐	☐	______
Transportation and transportation insurance	☐	☐	☐	☐	______

Part VII. Eliciting construction schedules - demonstration

Here, we would like you to please sketch appropriate construction schedules for various plant scenarios.
Below, we demonstrate the format in which we would like the answer to this question.

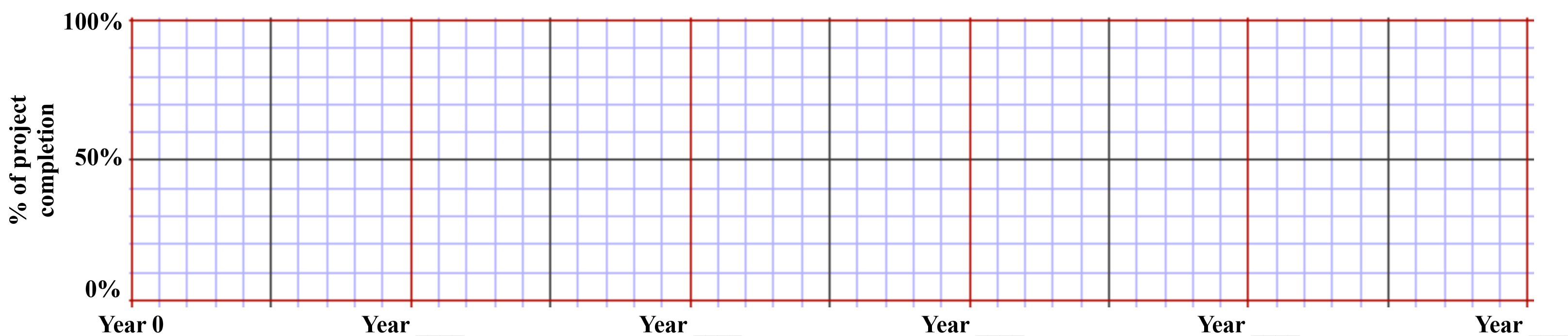
Scenario 0 **Demonstration**



Part VII. Eliciting construction schedules – conventional reactor plant

First, can you please sketch what would be, in your engineering judgment, an appropriate construction schedule for a conventional, 1,000MWe nuclear power plant construction project?

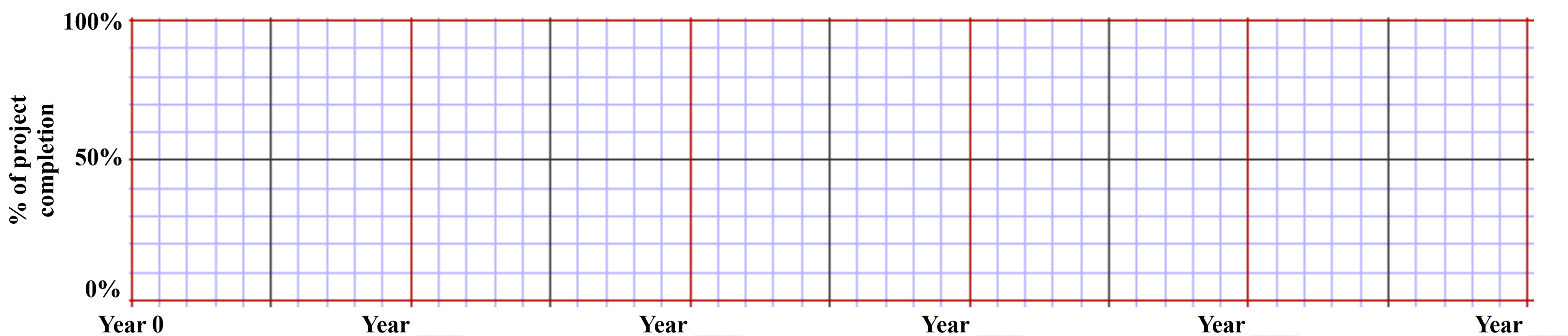
Scenario 1 **Plant with 1 GenIII+ conventional reactor** **1,000 MWe**



Part VII. Eliciting construction schedules – SMR number 1

Shorter construction schedules may reduce the cost of capital for SMR operators.
Can you please sketch what would be, in your engineering judgment, an appropriate construction schedule for one of the SMR number 1 plant scenarios we have been investigating?

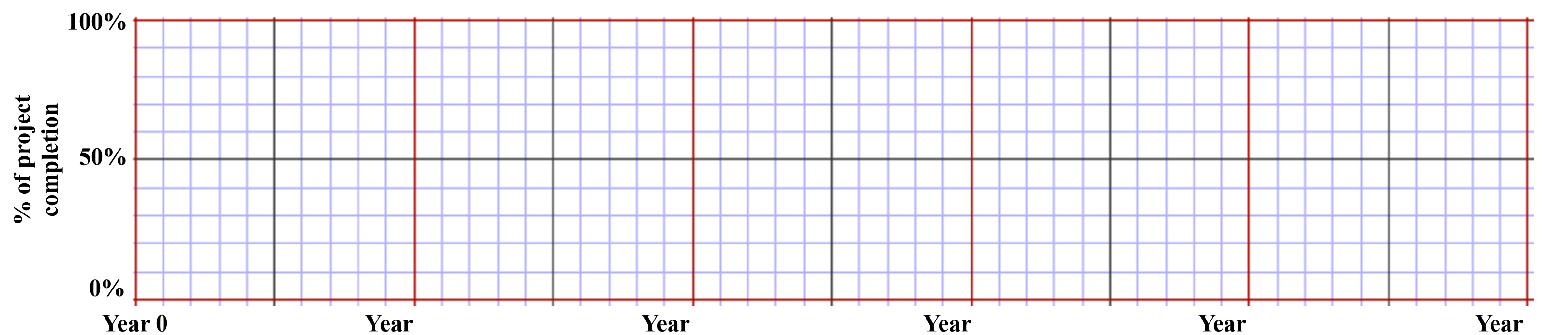
Scenario 2 **Plant with 1 x SMR 1** **45 MWe**



Part VII. Eliciting construction schedules – SMR number 2

Can you do the same for the one SMR number 2 plant scenario we have been investigating?

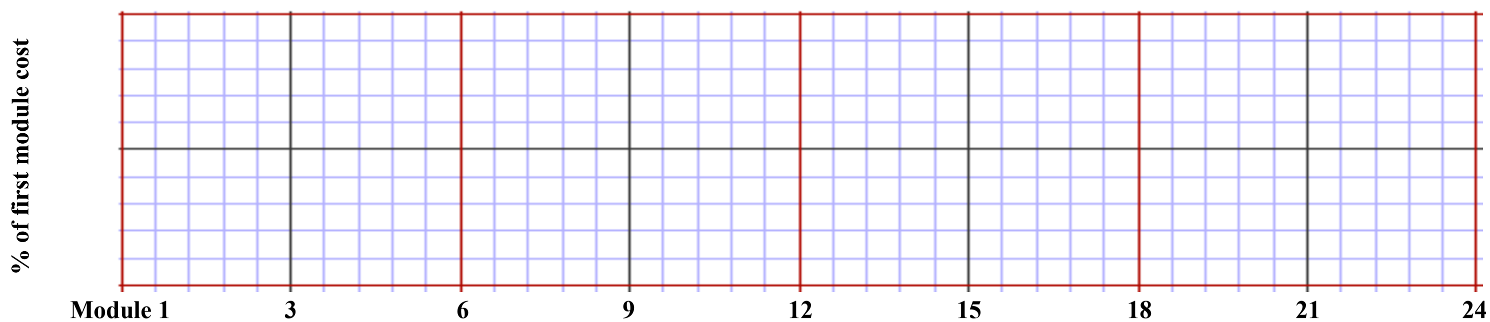
Scenario 5	**Plant with 1 x SMR 2**	**225 MWe**



Part VIII. What is the influence of modularity on SMR module costs?

How economically advantageous is the modularity of SMRs?
If we were to build SMR module **One** at site A, and then add modules incrementally – all at site A – how much of the cost of module **One** do we expect to incur with each incremental unit?

Scenario 0 **Demonstration**



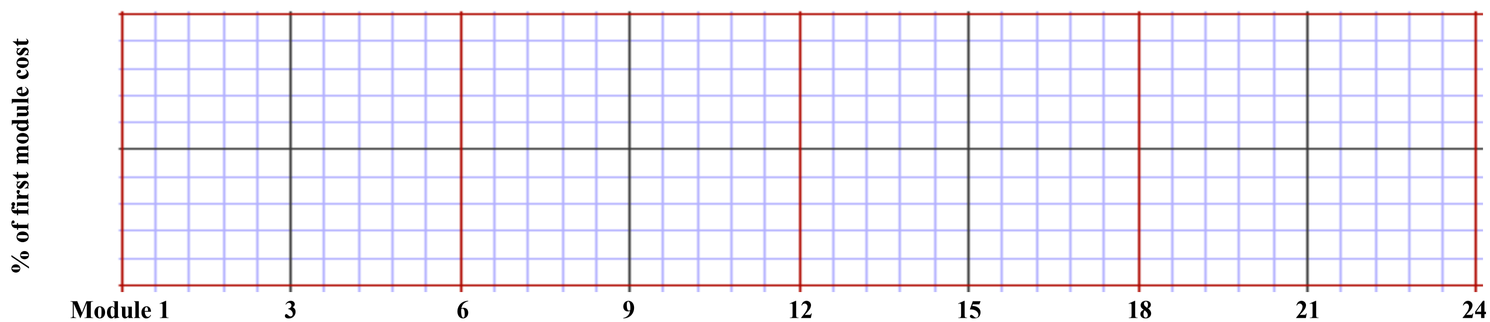
<u>When answering this question, please do the following:</u>

(1) Place a dot where you think the first module would be on the y-axis (at module 1)
(2) Draw the curve that corresponds to your estimate of modularity's influence on the capital cost of subsequent modules installed at the same site.

Part VIII. What is the influence of modularity on SMR number 1 module costs?

How economically advantageous is the modularity of SMRs?
If we were to build SMR module **One** at site A, and then add modules incrementally – all at site A – how much of the cost of module **One** do we expect to incur with each incremental unit?

SMR Number 1 **45 MWe modules**



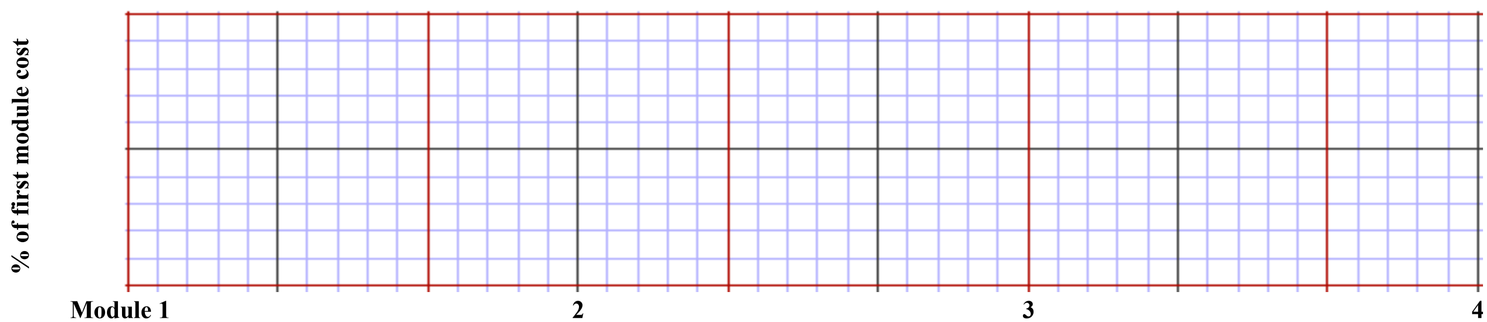
<u>When answering this question, please do the following:</u>

(1) Place a dot where you think the first module would be on the y-axis (at module 1)
(2) Draw the curve that corresponds to your estimate of modularity's influence on the capital cost of subsequent modules installed at the same site.

Part VIII. What is the influence of modularity on SMR number 2 module costs?

How economically advantageous is the modularity of SMRs?
If we were to build SMR module **One** at site A, and then add modules incrementally – all at site A – how much of the cost of module **One** do we expect to incur with each incremental unit?

SMR Number 2 **225 MWe modules**



<u>When answering this question, please do the following:</u>

(1) Place a dot where you think the first module would be on the y-axis (at module 1)
(2) Draw the curve that corresponds to your estimate of modularity's influence on the capital cost of subsequent modules installed at the same site.

Part IX. What do you envision as the perfect SMR deployment scenario?

We want to explore SMR siting options. Which combination of factors would – if achieved – constitute a 'best-case' scenario for SMR deployment? This is especially important as some SMR vendors are exploring the sale of such units to countries whose nuclear infrastructure is either not as developed as the United States', or is practically non-existent.

Can you comment on what the perfect SMR deployment scenario would look like? ______

Discuss regulatory institutions, security requirements, labor costs, energy needs, and cost of alternatives.

Political map of the world taken from http://www.unicist.net/partners-news/wp-content/uploads/2009/01/political-world-map-2007.gif. It is reproduced in black and white here.

Part X. Assessing the economic attractiveness of SMRs

Both academic studies and vendor materials tout the potential economic benefits of SMRs.
After studying the literature in depth, we have compiled a list of these benefits.
Here, we would like your opinion on these benefits: which do you think merit attention and more research, and which do not?

SMR-specific advantages we consider here are:	*Of no value*			*Of some value*			*Of utmost value*
Factory fabrication of reactor + NSSS	☐	☐	☐	☐	☐	☐	☐
Elimination of need for skeletal construction	☐	☐	☐	☐	☐	☐	☐
Inherent simplicity of design	☐	☐	☐	☐	☐	☐	☐
Different safety and planning costs	☐	☐	☐	☐	☐	☐	☐
More flexible sizing options	☐	☐	☐	☐	☐	☐	☐
More flexible siting options	☐	☐	☐	☐	☐	☐	☐
Shorter construction schedules	☐	☐	☐	☐	☐	☐	☐
Alternative end-use options	☐	☐	☐	☐	☐	☐	☐
Different decommissioning costs	☐	☐	☐	☐	☐	☐	☐
	Of no value			*Of some value*			*Of utmost value*

Part XI. Safety and security: challenges faced by SMRs

Two of the much-touted benefits of SMRs are that they, in theory, eliminate the risk of large-break LOCAs and incorporate many passive safety features. Here, we would like your opinion on which safety concerns are alleviated by SMR deployment (compared to conventional nuclear reactors) and which concerns are not.

Safety concerns we would like you to consider are:	*Of no concern*			*Of as much concern as large reactors*			*Of utmost concern*
Active sabotage (including proliferation)	☐	☐	☐	☐	☐	☐	☐
Large-break loss of coolant accidents	☐	☐	☐	☐	☐	☐	☐
Small-break loss of coolant accidents	☐	☐	☐	☐	☐	☐	☐
Operator training culture	☐	☐	☐	☐	☐	☐	☐
Spent fuel stockpile management	☐	☐	☐	☐	☐	☐	☐
Common mode failures	☐	☐	☐	☐	☐	☐	☐
Extreme, low-probability events	☐	☐	☐	☐	☐	☐	☐
Reactor design	☐	☐	☐	☐	☐	☐	☐
Adequacy of regulatory framework	☐	☐	☐	☐	☐	☐	☐
Maintenance culture	☐	☐	☐	☐	☐	☐	☐
Loss of off-site power	☐	☐	☐	☐	☐	☐	☐
	Of no concern			*Of as much concern as large reactors*			*Of utmost concern*

Part XII. Open-ended questions

Below, you will find a list of questions we would also like to explore.
You need not provide quantitative responses if that makes you feel uncomfortable.

Realistically, in terms of number of jobs required, what **percentage of site-work** do you expect to see eliminated thanks to inherent simplicity of SMR design?

Is the on-site work you eliminate particularly cost-intensive? If so, what **percentage of man-hours** do you expect to be eliminated thanks to inherent simplicity of SMR designs?

O&M costs: can fuel costs can be scaled by reactor output, given that fuel assembly design is exactly that of conventional reactors? Do you believe choosing a particular staffing scenario can have a significant impact on SMR plant operating costs?

If you were in charge of the NRC, what changes to the Commission's current approach to licensing SMR designs would you enact to accelerate the commercialization and deployment of SMRs of the light water variety?

What questions would you have liked us to ask?

Are there experts you know and would be comfortable having us speak to and include in this investigation?

Supplementary Information:

Appendix S3. Disaggregating the elicitation task using the IAEA code of accounts

A code of accounts is a numbering system that uniquely identifies the individual components of a project. In 2000, the International Atomic Energy Agency (IAEA) issued a technical report concerning the "economic evaluation of bids for nuclear power plants" (29). This was done to help those countries or non-nuclear utilities that wished to invite bids for nuclear plants but did not yet have a robust authority with its own accounts system that could evaluate such bids. Presumably, organs like the IAEA also put out this material to slowly nudge both existing and newly established organizations towards standardizing everything from the industry's jargon to the accounts system itself.

Section 4.2 and Annex I of the IAEA's report describe the Agency's accounts system in detail. Here, we are concerned with those components that fall within the scope of overnight cost. The IAEA labels these costs "fore costs." The description of these accounts, taken directly from the IAEA's report, is presented below. Overnight cost includes accounts 21 through 41, accounts 50 through 54, and account 70. The subset of accounts that we considered in this investigation is very close to the scope of overnight cost as defined by the IAEA. It included accounts 21 through 41 and account 50, but excluded accounts 51 through 54 and account 70, which fall under the scope of owner's cost. The code of accounts was further simplified to make it easier to digest by our experts, given the limited time we had with each.

We tried to be consistent when answering experts' queries as to where certain components, tools, or jobs fell in this classification scheme. One of the IAEA accounts system's departures from the code of accounts used by industry is its classification of construction labor and project management in a distinct category. Our experts suggested that vendors usually lump the labor required for the reactor plant, for instance, into the reactor plant category. Disaggregating labor from each of the components may have proved a challenge for our experts.

For a question whose purpose was to prompt discussion of the major cost drivers in SMR plants and how these compare to cost drivers in conventional plants, sorting through the code of accounts in full, while carefully outlining the particulars of an arbitrarily-chosen site, was deemed an ineffective use of what limited time we had with each expert. Also, there was no guarantee that such an exercise would have produced valuable information.

The twelve capital cost categories that fell under the scope just outlined were presented to the experts on index cards. These are presented below in list form. The experts were asked to rank the twelve items according to the share (in percentage terms) of capital cost that each would contribute to the total cost of a conventional nuclear power plant. The process was repeated for a generic, one-unit SMR plant. Specifically, we were interested in changes in the ranking. We then asked our experts for the percentage of capital cost that the five top-ranked categories account for in each of the five scenarios under investigation.

Table S2 lists the five top-ranked items for both a conventional nuclear plant and a generic, one-unit SMR plant, according to each of the experts who responded to this question. Reactor plant equipment is the one category that is ranked in the top five by all experts (for both conventional and SMR plants). All experts believe that the share of capital cost accounted for by reactor plant equipment is higher for SMR plants than it is for conventional plants. Four other categories are present in more than half of the responses for a conventional plant. These are (1) turbine plant equipment, (2) building and site preparation, (3) electrical equipment and I&C plant equipment, and (4) construction labor, project management, facilities, and tools. For a conventional nuclear plant, the last of these is ranked highest by almost half of the experts. The proportion of cost accounted for by construction labor is lower for SMR plants, thanks to the fewer number of labor-intensive jobs needed at an SMR construction site. Experts agreed that this is one of the fundamental benefits of SMRs. Building and site preparation is assigned a lower share of capital cost in SMR plants as well, and it drops out of the top five in some experts' judgment. On the other hand, electrical equipment and I&C plant equipment generally accounts for a greater share of capital cost in an SMR plant, as it is the same equipment you would need in a conventional plant. While there is commonality in the rankings, the issue is hardly cut-and-dry: seven out of the twelve categories feature in ranks one to three for both conventional and SMR plants.

The percentage of capital cost that the five top-ranked items account for in a conventional 1,000MW_e Gen III+ plant ranges from 50% to 90%, with general consensus centering on two-thirds to three-quarters of total project cost, as Figure S3 shows. A similar lack of consensus exists for the four SMR scenarios. We engaged in a substantial discussion with each expert regarding the cost of multi-module facilities. Some believed that, with twenty-four SMRs on a single site, the cost of the twenty-four reactor modules would dominate the total project cost. Others vehemently disagreed, suggesting that the operation-construction interface for such a facility would require a large staff. The common theme we found is that, while some SMR-specific advantages may reduce the costs of particular components or systems, these effects may be cancelled out by potential cost inflation in other areas.

The twelve capital cost categories under consideration are listed below, along with a short summary of what each entails. This list is adapted from the report in question (29):

1) **Building and site preparation**

    - *Land reclamation, clearing, and grading*
    - *Access roads, sidewalks, access roads connected with public roads*
    - *Railway access*
    - *Sanitary installations, yard drainage*
    - *Storm sewer systems, waterfront structures*
    - *Harbor and cranes, waterway improvements*
    - *Air access facilities*
    - *Excavation and foundation for buildings*

2) **Reactor plant equipment**

- *Reactor vessel and accessories*
- *Studs, fasteners, seals, gaskets, tubes, and fittings*
- *Reactor vessel internals (core tank, baffles, shrouds, moderators, reactivity control components, upper core structure, CR guide assemblies, distributors, etc.)*
- *Reactor vessel support structures*
- *Reactor control devices (CRDMs, in-core instrumentation, neutron sources, boron shutdown systems)*
- *Main heat transfer and transport system (coolant system)*
- *Reactor auxiliary systems*
- *Reactor ancillary systems*
- *Nuclear fuel handling and storage systems*

3) Turbine plant equipment

- *High pressure and low pressure turbines*
- *Turbine drain system; seal steam/leak off system*
- *Moisture separator/reheater system*
- *Turbine bypass system*
- *Lubrication and control fluid system*
- *Ancillary equipment (main stops, throttles, valves, piping, insulation, instrumentation, etc.)*
- *Support structures, foundation, mechanical parts*

4) Generator plant equipment

- *Generator*
- *Water system*
- *H_2 system*
- *CO_2 system*
- *N_2 system*
- *Lubrication system*
- *Seal oil system*
- *Excitation system*

5) Condensate, feedwater, and main steam system

- *Main condensate, feedwater, and main steam systems*
- *Piping*
- *Valves and fittings*
- *Supports (piping related)*
- *Insulation*
- *Pumps, storage tanks, and heaters*
- *Emergency feedwater system*

6) Water intake and water rejection

- *Circulation water intake canals, works, structures, etc.*
- *Water pump structures (circulation, service, process cooling pumps)*
- *Water overflow structures, surge tanks, discharge canals*
- *Circulation water aeration structures, water surge ponds*

- *Cooling water structures, tower pump structures, connection structures, and discharge structures*
- *Circulation water piping*

7) Electrical equipment and I&C plant equipment

- *Bus ducts, breaker systems, and switchgear*
- *DC distribution and sub-distribution equipment*
- *Batteries and chargers*
- *Converters and inverters, plus control and monitoring*
- *Earthing equipment*
- *Diesel and diesel control equipment*
- *Aux equipment: transformers, motors, cables, penetrations, junction boxes, supporting structures*
- *Ancillary and communication systems*
- *Sensors, signal processing equipment, computers, monitoring equipment, instrumentation equipment*

8) HVAC and fire fighting equipment

- *Ventilation and air conditioning systems for reactor building, reactor auxiliary building, and fuel building (those buildings that are in controlled areas)*
- *Ventilation and air conditioning systems for those buildings that are not in controlled areas*

- *Both of the above include filters, heaters, coolers, fans, blowers, humidifiers, ducts, piping, valves, and other equipment (motors and actuators)*
- *Alarm and sprinkler systems, plus piping and valves*
- *Mobile installations*
- *Manually operated fire fighting equipment*

9) Site equipment (cranes, hoists, elevators, etc.)

- *Polar crane inside reactor building*
- *Gantry crane outside reactor building*
- *Cranes in turbine building*
- *Cranes in reactor auxiliary building*
- *Elevators in reactor building*
- *Elevators in reactor auxiliary building*
- *Elevators in electrical building*
- *Laboratory equipment*

10) Engineering, design, and layout services

- *Civil engineering, general plant layout and design*
- *Mechanical engineering for systems and components*
- *Electrical engineering for systems and components*
- *I&C and reactor protection engineering*

- *Reactor physics, thermodynamics, thermohydraulics, plant dynamics, analogue computer analysis, earthquake analysis, chemistry and other engineering activities not directly component or system related*
- *Construction and/or erection manuals and instruction preparation, commissioning instructions, operation procedures, as well as quality assurance measures*

11) Construction labor, project management, facilities, and tools

- *Civil works, mechanical systems, electrical systems*
- *Administration, cost control, contracting, scheduling*
- *Quality assurance*
- *Field offices with installation, social buildings, warehouses, workshops, guard houses, and fences*
- *Provisional installation during construction*
- *Fuel for engines, turbines, and boilers*
- *Waste storage and treatment*
- *Communication equipment*
- *Heavy construction equipment*

12) Transportation and transportation insurance

- *Harbor crane*
- *Gantry*
- *Unloading equipment*

- *Lorries*
- *Scaffolds, ladders, and stairways*

Figure Legends:

Figure S3: Share (percentage) of capital cost accounted for by the five top-ranked categories when constructing conventional and SMR plants. Note that the information is presented by expert, and not by scenario, because expert rankings differ. In other words, rankings are comparable across scenarios for each individual expert, but not across experts.

Figure S3

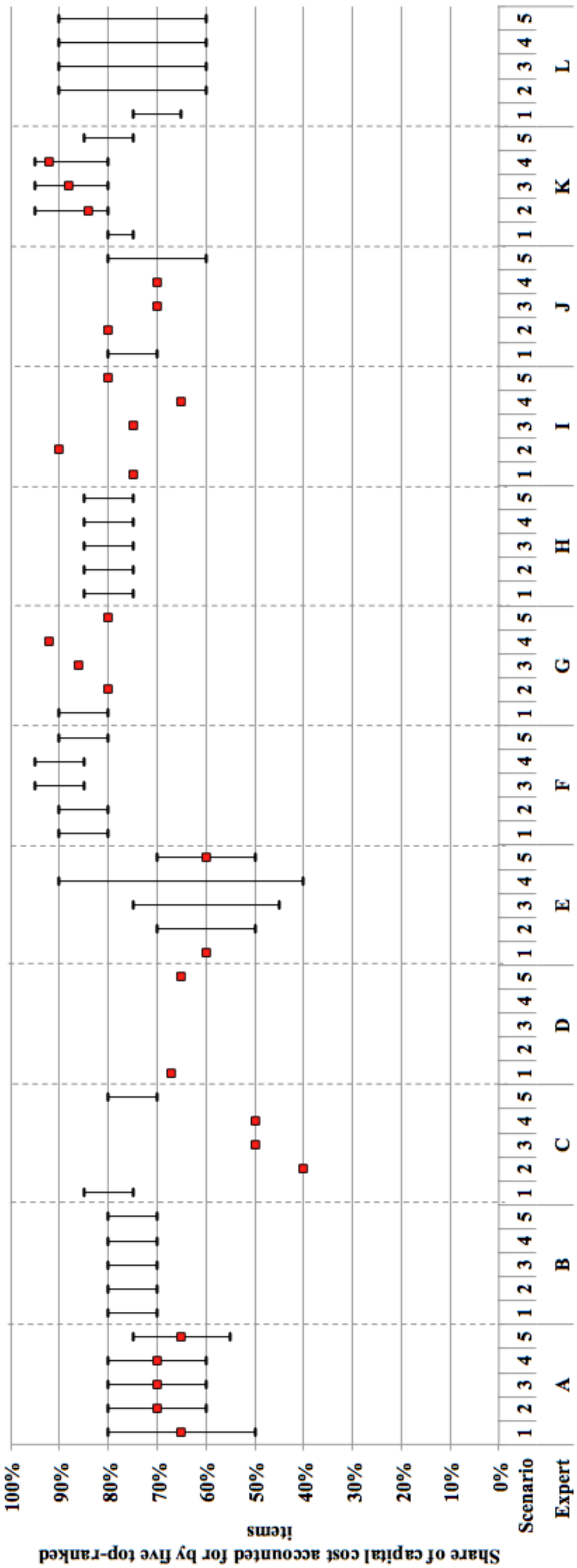

Share of capital cost accounted for by five top-ranked items
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Scenario
Expert
A
B
C
D
E
F
G
H
I
J
K
L

Table S2: *Experts were asked to rank the twelve capital cost items in the IAEA's Code of Accounts by the share of capital cost each accounts for both in a typical, 1,000MW$_e$, Gen III+ nuclear plant and in a generic, one-unit SMR plant.*

	Five top-ranked items in a typical, 1,000MWe, Gen III+ nuclear plant					Five top-ranked items in a generic, one-unit SMR plant					Legend	
Rank	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**Code**	**Item**
A	RPE	EIC	CFS	TPE	GPE	RPE	EIC	TPE	GPE	CFS	BSP	Building and site preparation
B	CPM	BSP	RPE	TPE	EIC	RPE	CPM	BSP	TPE	EIC	RPE	Reactor plant equipment
C	RPE	TPE	CPM	BSP	EDL	RPE	CPM	EIC	TPE	BSP	TPE	Turbine plant equipment
D	CPM	RPE	TPE	CFS	EIC	RPE	TPE	CPM	CFS	EIC	GPE	Generator plant equipment
E	CPM	RPE	EDL	BSP	TPE	RPE	EDL	CPM	TPE	GPE	CFS	Condensate, feedwater, and main steam system
F	RPE	TPE	BSP	CPM	EDL	BSP	CPM	RPE	TPE	GPE	WIR	Water intake and water rejection
G	RPE	BSP	TPE	CPM	EDL	BSP	CPM	RPE	TPE	EIC	EIC	Electrical equipment and I&C plant equipment
H	RPE	TPE	BSP	CPM	EIC	BSP	CPM			EIC	HVC	HVAC and fire fighting equipment
I	EIC	CPM	EDL	RPE	GPE	EIC	CPM	EDL	RPE	GPE	SEQ	Site equipment (cranes, hoists, elevators)
J	CPM	RPE	TPE	BSP	EIC	RPE	CPM	BSP	TPE	WIR	EDL	Engineering, design, and layout services
K	RPE	CPM	EDL	TPE	BSP	RPE	CPM	EDL	TPE	BSP	CPM	Construction labor, project management, facilities, and tools
L	CPM	BSP	RPE	TPE	CFS	CPM	RPE	WIR	TPE	BSP	TTI	Transportation and transportation insurance

Supplementary Information:

Appendix S4. More details about the expert elicitation

Developing the protocol:

We started with a list of the questions we wanted answered. After several rounds of discussion among the authors, each of which resulted in the iterative expansion of certain areas of inquiry, their exclusion, or the refinement of the questions, we settled on queries related to the following areas:

1. capital costs of each of the five scenarios we developed;
2. the probability that the costs for each scenario would fall below certain target costs;
3. each single-unit SMR's construction duration;
4. the components that account for most of the cost of an SMR project;
5. expert judgments on where in the world these reactors could see first-of-a-kind and nth-of-a-kind deployment; and,
6. a general list of open-ended questions designed to stir discussion.

Once the protocol was completed, we conducted a set of pilot interviews with non-experts. These were designed to highlight problems in the interviewer's delivery or in the phrasing of the questions. As a result of what we learned in these interviews, we rephrased some questions to better delineate the scope of the investigation, we added a 'background' section to provide as much reference information as the pilot testers deemed necessary to absorb the tasks, and we noted the need for visual aids to help guide the experts through the protocol. Consultations with researchers in behavioral social science raised methodological questions regarding the structure of response forms and visual aids. After further revisions, additional pilot testing was carried out, this time with an expert from the pool of experts we had been building during the course of the protocol's development. Because experts have demanding schedules, we constrained the protocol so that it took around two hours. In the end, interviews took between one and four hours. Necessarily, a balance had to be struck between items that went on the protocol forms and those that were verbally relayed to each expert. Interviews were recorded and transcribed manually by the authors (we decided against using software in order to catch the nuances that different intonations suggested. Also, the software we tried had obvious problems with the terminology and acronyms that were employed). Where transition words and silence-fillers (like "umm") were deliberately uttered to express hesitation about a prompted claim, this was usually brought up in the course of the interview and duly noted in the transcripts using brackets. Upon transcription, audio files were deleted.

Addressing the pitfalls of expert elicitation:

Pitfalls such as over confidence, and the bias that cognitive heuristics can produce arise in any process involving human judgment about uncertainty. The difference in a well-designed expert elicitation is that one can adopt strategies designed to minimize their influence. Strategies we employed included: 1) prompting experts to justify their estimates and 2) asking for probabilistic judgments in more than one way, checking for consistency in the process. Below, we walk through one example of such an elicitation for illustrative purposes. The procedure followed was that pioneered by Morgan and Henrion (10) that provides a more comprehensive treatment.

Assume an expert provided a lower bound estimate for the capital cost of a scenario when prompted. We then asked them to explain why they thought that number was correct (regardless of what it was). For example, if an expert provided a lower bound of $3,000 per kW_e, we asked why it could not be lower. We might say: "Suppose the number actually turns out to be $2,500, can you suggest a way in which that might happen?" The purpose of this prompting exercise was to expand the universe of alternatives that the expert considered. This process was repeated for the upper bound. In either case, if the expert revised their estimate, they were effectively considering a more complete universe of alternatives than they previously had, which means their revised range was less overconfident than their original range. The expert may stick to their original range after prompting from the interviewer, which is also fine: the interviewer's job was to prod and caution experts about overconfidence (each interview was preceded with a discussion of what overconfidence is and how it manifests itself in such procedures), *not* to coerce the expert into providing a wider range. In order to avoid "anchoring," the interviewer elicited the median, or "best," estimate last.

The second method we used to avoid overconfidence was a consistency check. In our case, once we had elicited a range of estimates of capital cost for each scenario, we proceeded to a seemingly different question that asked experts for the probability of capital costs for each scenario (a) falling below \$4,000 per kW_e and (b) rising above \$6,000 per kW_e. By answering these two questions, however, the expert provided us what we needed to construct a cumulative distribution function (CDF) that we could then compare to the probabilistic judgments provided in response to the first question above. If the two CDFs generated two different pictures of capital cost, the inconsistency was brought to the expert's attention, and they were asked to revise their estimates.

The above discussion demonstrates the importance of developing a well-specified system for the elicitation, hence our emphasis on the technical depth that went into developing each scenario. This supports our argument that, in the context of energy technologies, asking simply for estimates of "solar panel costs" or "SMR costs" is inappropriate.