Exploring the Deployment Potential of Small Modular Reactors

Submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Engineering and Public Policy

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May 2014

Acknowledgments

I would like to thank my advisors, Granger Morgan and Inês Azevedo, for the guidance and support they have provided over the past four years. Their intelligence, their confident yet subdued persuasion, their intellectual curiosity, their humility, and their wit have made me a better researcher and a better human being. It was an honor to work with them, and I owe them a debt of gratitude that cannot be repaid. I would also like to thank Jay Apt, discussions with whom never fail to get to the crux of the matter, and always leave me with plenty to ponder. My gratitude also goes to Andreas Pautz, Shikha Prasad, Keith Florig, Marie-Valentine Florin, and Nadeja Victor for the valuable support they have provided during my doctoral studies.

I am confident that some of my EPP colleagues will remain lifelong friends. My thanks go to Shelly, Raul, Mohamed, Ivonne, Olga, Parth, Santosh, Will, and Kristen. They proofread my work, and oftentimes distracted me from it with conversations as varied as the merits of olive oil, proper squash technique, the superiority of Bach over almost everyone else, and the nuances of politics and theology. We found the humor and value in each of these discussions (well, except the one about olive oil), and I will treasure them forever. I must also thank EPP staff: Patti, Vicki, Barb, and Adam, especially. Their patience, their magnanimity, and their support were as forthcoming and invaluable in August 2010 as they are in these crucial days.

Finally, my gratitude goes to my parents and to my brother, Feras. Putting up with me is a difficult task; during these past few years, I made it positively Herculean. I love them very much.

This work was supported in part by the Bahraini Crown Prince's International Scholarship Program, the Steinbrenner Institute at Carnegie Mellon, and the Center on Climate and Energy Decision Making (SES-0949710), which is funded through a cooperative agreement between the National Science Foundation and Carnegie Mellon. It was also supported by a grant from the

John D. and Catherine T. MacArthur Foundation (12-101167-000-INP). The support of the Carnegie Mellon Electricity Industry Center must also be acknowledged.

Abstract

This thesis reports the results of several investigations into the viability of an emergent technology. Due to the lack of data in such cases, and the sensitivity surrounding nuclear power, exploring the potential of small modular reactors (SMRs) proved challenging. Moreover, these reactors come in a wide range of sizes and can employ a number of technologies, which made investigating the category as a whole difficult.

We started by looking at a subset of SMRs that were the most promising candidates for near to mid-term deployment: integral light water SMRs. We conducted a technically detailed elicitation of expert assessments of their capital costs and construction duration, focusing on five reactor deployment scenarios that involved a large reactor and two light water SMRs. Consistent with the uncertainty introduced by past cost overruns and construction delays, median estimates of the cost of new large plants varied by more than a factor of 2.5. Expert judgments about likely SMR costs displayed an even wider range. There was consensus that an SMR plant's construction duration would be shorter than a large reactor's. Experts identified more affordable unit cost, factory fabrication, and shorter construction schedules as factors that may make light water SMRs economically viable, though these reactors do not constitute a paradigm shift when it comes to nuclear power's safety and security.

Using these expert assessments of cost and construction duration, we calculated levelized cost of electricity values for four of the five scenarios. For the large plant, median levelized cost estimates ranged from \$56 to \$120 per MWh. Median estimates of levelized cost ranged from \$77 to \$240 per MWh for a 45MW$_e$ SMR, and from \$65 to \$120 per MWh for a 225MW$_e$ unit. We concluded that controlling construction duration is important, though not as important a

factor in the analysis as capital cost, and, given the price of electricity in some parts of the U.S., it is possible to construct an argument for deploying SMRs in certain locations.

We then decided to investigate the technical and institutional barriers hampering the development and deployment of a subset of six SMRs, including two light water designs and four non-light water advanced designs. We organized an invitational workshop that became an integrated assessment of various designs and of the institutional innovations required to bring SMRs to market.

Some valuable insights were gleaned from the workshop: there is consensus that many of the challenges facing advanced SMRs are rooted in institutional biases in favor of the light water economy, as opposed to technical ones. The institutional factors that are judged to pose the greatest challenge to the mass deployment of SMRs are: the lack of a greenhouse gas control regime; political and financial instability; public concerns about nuclear safety and waste; and inadequate national and international institutions.

When asked what factors most help promote SMR adoption in OECD and developing countries, economic factors dominate the list of characteristics that most contribute to their promotion in OECD countries but, when it comes to developing countries, institutional factors are regarded as being of highest import. Safety of design and safety in operation are judged the most important characteristic on both lists.

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List of abbreviations

ABM	Anti-ballistic missile
AEC	U.S. Atomic Energy Commission
BAU	Business as usual
B-O-O	Build-own-operate
BWR	Boiling water reactor
B&W	Babcock and Wilcox
CCS	Carbon capture and sequestration (or carbon capture and storage)
CDF	Cumulative distribution function
CFR	Code of Federal Regulations
CPI	Consumer price index
DFA	Decommissioning funding allowance
DOE	U.S. Department of Energy
EIA	Energy Information Administration, an agency of the U.S. Department of Energy
EM^2	Energy Multiplier Module
EOR	Enhanced oil recovery
EPC	Engineering, procurement, and construction
EPZ	Emergency planning zone
EU	European Union
FNPP	Floating nuclear power plant
FOAK	First-of-a-kind
GCC	Gulf Cooperation Council
Gen III+	Generation III+ (i.e. current-generation) reactor
HR	Heat rate
HTR	High temperature reactor
HTR-PM	High temperature reactor – pebble bed module
HWR	Heavy water reactor
IAEA	International Atomic Energy Agency
INPO	Institute of Nuclear Power Operations
iPWR	Integral pressurized water reactor
IRGC	International Risk Governance Council
kW_e	Kilowatt-electric
kWh	Kilowatt-hour
LAC	Levelized annual cost
LCOE	Levelized cost of electricity
LEU	Low-enriched uranium (enrichment level < 20% ^{235}U)
LMR	Liquid metal reactor
LWR	Light water reactor
MACRS	Modified Accelerated Cost Recovery System
MC&A	Material control and accounting
MIT	Massachusetts Institute of Technology
MW_e	Megawatt-electric
MWh	Megawatt-hour
NEI	Nuclear Energy Institute

NOAK	N^{th}-of-a-kind
NPP	Nuclear power plant
NPT	Nuclear non-proliferation treaty
NRC	Nuclear Regulatory Commission
NSG	Nuclear Suppliers Group
NSSS	Nuclear steam supply system
OECD	Organization for Economic Co-operation and Development
O&M	Operation and maintenance
PSI	Paul Scherrer Institute
PTBT	Partial Test Ban Treaty
PWR	Pressurized water reactor
RPV	Reactor pressure vessel
SDR	Special drawing rights
SG	Steam generator
SLR	Subsequent license renewal
SMR	Small modular reactor
SNM	Special nuclear material
START	Strategic Arms Reduction Treaty
TRISO	Tristructural-isotropic
UO_2	Uranium dioxide
URD	Utility requirements document
WACC	Weighted average cost of capital
WANO	World Association of Nuclear Operators
WMD	Weapons of mass destruction

Chapter 1: Introduction

Close to sixty years after the Shippingport Atomic Power Station was commissioned, today's nuclear power plant (NPP) builds must contend with the same concerns that were raised against the earliest units. These can be broadly divided into four categories: the high capital cost associated with constructing them, the safety of reactor operations, the management of the resulting spent fuel stockpile, and the potential diversion of nuclear materials for weapons proliferation. As the world gained greater operational experience with nuclear power, both the technology and the institutions that governed it evolved to try and alleviate each of these concerns, with mixed results.

Despite early attempts to develop and deploy a number of technologies, nuclear operators worldwide had, for a number of reasons, settled on light water designs less than two decades after Shippingport was commissioned (1). These reactors, the first units of which were uprated versions of early submarine propulsion units, use regular water as both coolant and moderator and continue to dominate today's NPP fleet: currently, 355 of the world's 435 operating commercial reactors (82%) are either pressurized water reactors (PWRs) or boiling water reactors (BWRs) (2).

In a large PWR's reactor pressure vessel (RPV), uranium dioxide (UO_2) pellets in the core, enriched to 4.95% ^{235}U and packed into a fuel rod, engage in nuclear fission reactions that heat up the water around them. This water, which is pressurized to keep it in its liquid state, flows from the RPV to one or more steam generators (SGs), where it interacts with a secondary loop of water; this heat exchange boils the water in the secondary loop. The steam is channeled to a turbine, which turns a generator that produces electricity (3, 4). In a BWR, there is only one water loop: the water that is heated up by the core is turned to steam and channeled to the turbine directly (4, 5).

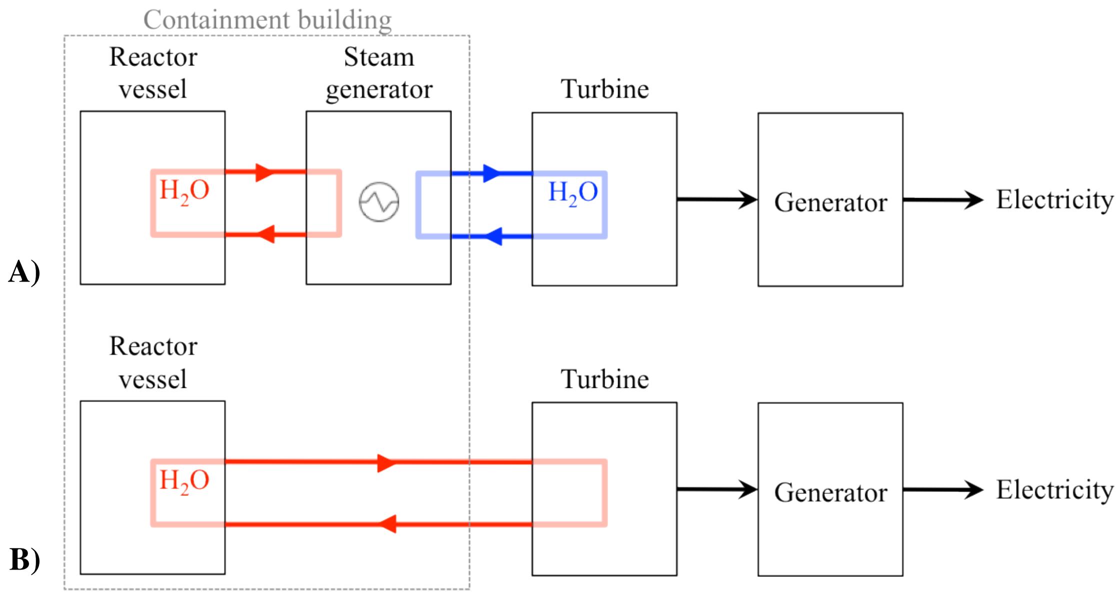


Figure 1. Schematic flow diagrams of A) a pressurized water reactor and B) a boiling water reactor.

One thing that changed dramatically was the power output of these units. By 1968, eleven years after the 68 Megawatt-electric (MW_e) Shippingport was commissioned, utilities were ordering units that produced ten times as much power in an effort to improve plant economics (6). The current global commercial NPP fleet has an average power output of 850MW_e (7); figure 2 below shows the increase in individual unit output over time. Harnessing economies of scale in reactor output quickly became conventional wisdom in the nuclear industry, and this has not changed since: the large light water reactors (LWRs) currently on the market, referred to as Generation III+ (Gen III+) reactors, produce anywhere from 1,000MW_e to 1,600MW_e (8).

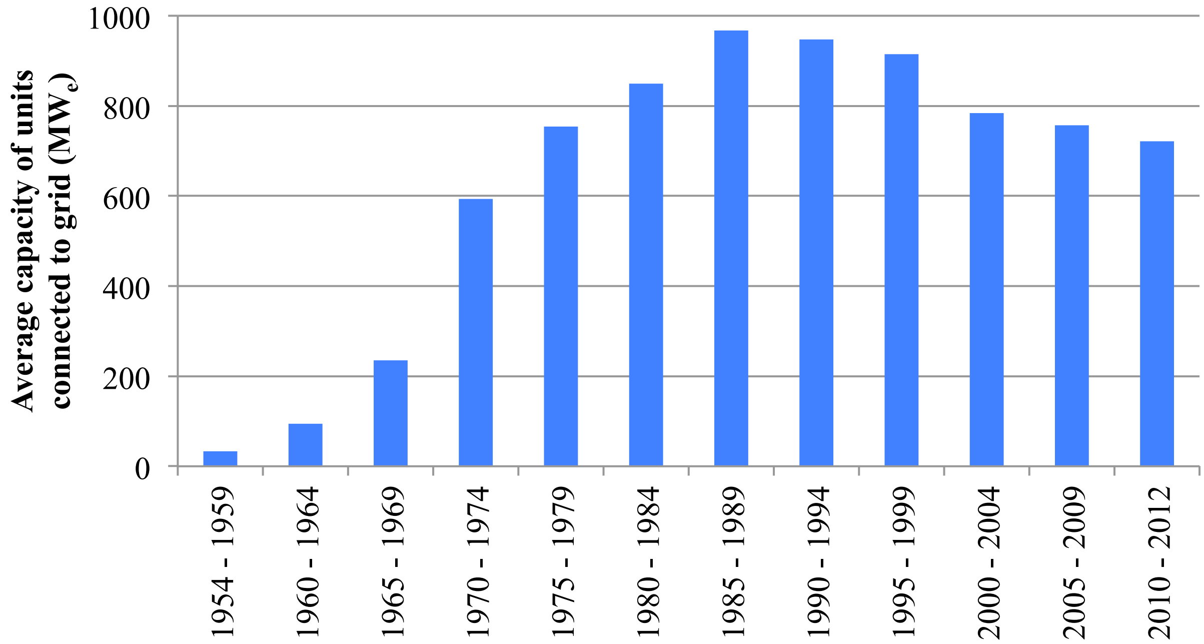


Figure 2. Average unit output increased from 34MW_e with the first batch of 11 reactors connected to the grid in 1954-1959 to 750MW_e two decades later (6). The Indian and Chinese NPP construction efforts are responsible for the decrease in average unit output at the turn of this century. These relied on small and medium-sized reactors such as the 220MW_e Indian heavy water reactor (PHWR-220), the 610MW_e Chinese Nuclear Plant (CNP-600), and the 650MW_e Chinese CANDU-6. China and India are also constructing Gigawatt-scale plants.

There are complexities associated with building such large plants, and the concentration on economies of scale in reactor output led to other economies being overlooked. Economies of volume that could have changed the reactor fabrication paradigm through mass-production were never exploited, for example. Also, the industry did not change the deployment paradigm by exploiting modular construction; the majority of these designs need to be "stick-built": in other words, they are constructed mostly on-site. The same could be said for supply chain economies: the demand for bigger and heavier-duty components, as well as expensive quality control and quality assurance measures, squeezed out all but the largest and most capable firms from the nuclear supply chain, granting them the freedom to command price premiums on components.

This applied to everything from RPVs to steam turbines that could manage the output of a unit rated at more than 1,000MW_e (9–11).

These complexities were compounded by new, stricter regulations that inevitably came into force after every nuclear incident, which made "spreading out" the capital cost over a larger power output even more important. The result of all this was a measurable slow-down in the rate of NPP construction starts at the turn of the 1980s, a trend illustrated in figure 3. Construction starts in the United States virtually stopped after the accident at Three Mile Island in 1979. In fact, construction on all 100 commercial reactors currently operating in the United States began prior to the accident (12). The rate of construction worldwide has remained slow over the past three decades. There were 40 construction starts in the 1950s, 139 in the 1960s, and 305 in the 1970s. Later decades saw a remarkable reversal of the trend: there were 136 construction starts in the 1980s and only 29 in the 90s. The number of starts increased to 54 in the 2000s, mostly due to China's growing energy demand (6). The median age of today's NPP fleet is thus 30 years (13), which has great implications for the near-term future of nuclear power given the 40-year lifetime proposed by nuclear technology vendors for these units. Acknowledging this fact, nuclear operators and licensing authorities are extending the life of their plants by another 20 years where possible. An option for a further 20-year renewal remains on the table in the United States, and efforts to study the viability of such "subsequent license renewals" (SLRs) are underway (14).

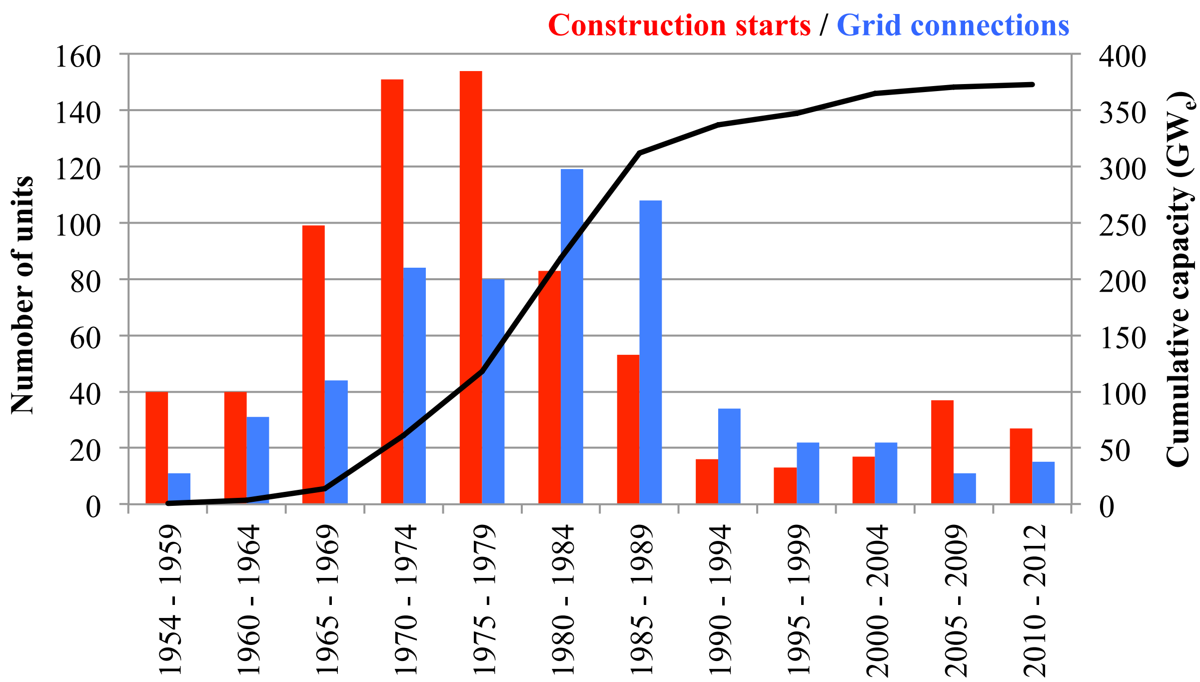


Figure 3. Trends in NPP construction over time. After a promising early start, NPP construction slowed, markedly after the first serious nuclear accident at Three Mile Island in 1979 (6). Concern about greenhouse gas emissions, and rising demand in China, have fueled an increase in NPP construction, though the Fukushima disaster proved how fragile this "renaissance" is.

Despite its age, the current fleet of nuclear power plants remains responsible for 12% of the world's total electricity production; in the U.S., its share is closer to 19% (15). Nuclear power remains a proven way of generating carbon-free base load electricity at large enough scales to address the climate problem we face. Given the sheer scale of the climate crisis, and hence of the challenge facing our carbon-intensive energy system, it is hard to see how a nuclear-free generation portfolio can possibly accomplish the task of mitigating greenhouse gas emissions (16–18). The problem is compounded when we consider the complications of intermittency and variability that arise with most other sources of renewable energy (16–18). Recognizing this, environmental scientists and activists, including ones who were previously anti-nuclear, have over the past decade advocated the expanded use of nuclear energy in an effort to decarbonize the power system (19–21).

If nuclear power really is to become an essential contributor to our future energy system, it must prove itself a more viable option than it is now, which necessitates a radical change in the industry. The past decade has seen growing interest in the development and deployment of a new generation of small modular nuclear reactors (SMRs), which would ideally shift the nuclear industry towards a paradigm of factory fabrication akin to that of the aircraft industry. The latter is a model of an industry that serially manufactures highly complex and heavily regulated products. The ultimate aim is not only to better manage cost and construction duration, but also to ensure high levels of quality control. It has been argued that if aircraft were made and certified one at a time, in the way nuclear reactors have been built and certified in the U.S., "many travelers would find the level of safety unacceptable and air travel would be much more expensive…pilots and mechanics would have to be specially trained to operate each aircraft…many replacement parts would have to be custom made…[and] every time an aircraft experienced a problem engineers and managers would be unsure how to extrapolate the lessons to other aircraft…" (22) If they fulfill their promise, SMRs might stand a chance of becoming part of a portfolio of carbon-free energy sources, but investigating them at such an early stage poses challenges of its own, since they come in a wide variety of technologies and in a wide range of sizes. In the next chapter, we compare conventional reactors to SMRs and introduce the main types of SMRs currently in development worldwide. We then highlight the potential advantages and disadvantages of the technology. In chapter 3, we review the history of nuclear economics, including cost forecasting, and investigate the anticipated capital cost of constructing light water small modular reactors. In chapter 4, we develop estimates of the levelized cost of these reactors using capital cost and construction duration estimates from chapter 3. Using these results, we try to anticipate where these reactors might find a viable market. Chapter 5 summarizes the results of a workshop we organized on the technical and institutional barriers hampering the development and deployment of SMRs. Chapter 6 synthesizes the results of the previous chapters and presents something of a roadmap for action, before closing with the conclusions of our work.

Chapter 2: Overview of small modular reactor designs

This section is meant to be a primer to the types of reactor technologies that will be discussed throughout this document. It makes no claims regarding the advantages and disadvantages of any one technology. Obviously, not only is each technology different, but each also necessitates rather different processes on both the front-end and the back-end of the nuclear fuel cycle. The challenges of each of the steps in this cycle – technical, economical, political, and institutional – are the reasons for the continued dominance of LWRs. At least in the case of LWRs, many of the technical and institutional barriers have been resolved in existing nuclear energy states.

The International Atomic Energy Agency (IAEA) classifies any nuclear reactor with a power output of less than $300MW_e$ as small. Those with outputs between 300 and $700MW_e$ are considered medium-sized reactors, while those with outputs greater than $700MW_e$ are classified as large reactors (23). We concentrate on small reactors in this dissertation, and use the acronym to refer to small modular reactors, as does the U.S. Department of Energy (DOE) (24). SMRs come in a wide range of sizes and adopt a wide range of technologies. These range from $180MW_e$ light water SMRs (25) that adopt the same operational principles as their larger counterparts and are designed to power towns, to $25MW_e$ liquid metal reactors (26) that are designed to replace diesel generators, whether in remote areas or for military or disaster-response purposes. Table 1 below lists 26 SMR designs currently in development worldwide. Below, we provide a brief overview of the four categories of nuclear technology under which these 26 SMR designs fall: light water reactors, heavy water reactors (HWRs), high temperature reactors (HTRs), and liquid metal reactors (LMRs).

Table 1. A list of small (<300MW$_e$) reactor designs, sorted alphabetically by country, then by name. iPWRs are integral PWRs, an SMR type that will be introduced below.

No.	Name	Developer	Country	Type	Capacity (MW$_e$)
1	CAREM-25	CNEA	Argentina	iPWR	25-150
2	FBNR	FURGS	Brazil	PWR	72
3	ACP100	CNNC	China	iPWR	100
4	CEFR	CNEIC	China	LMR	20
5	CNP-300	CNNC	China	PWR	300
6	HTR-PM	Tsinghua Univ.	China	HTR	105
7	Flexblue	DCNS	France	PWR	50-250
8	AHWR300-LEU	BARC	India	HWR	304
9	PHWR-220	NPCIL	India	HWR	220
10	4S	Toshiba	Japan	LMR	10
11	SMART	KAERI	Korea	iPWR	100
12	ABV-6M	OKBM	Russia	PWR	8.6
13	BREST-OD-300	RDIPE	Russia	LMR	300
14	KLT-40S	OKBM	Russia	PWR	35
15	RITM	OKBM	Russia	iPWR	50
16	SHELF	NIKIET	Russia	PWR	6.0
17	SVBR-100	JSC AKME	Russia	LMR	100
18	UNITHERM	RDIPE	Russia	PWR	2.5
19	VK-300	RDIPE	Russia	BWR	250
20	WWER-300	OKBM	Russia	PWR	300
21	EM^2	General Atomics	USA	HTR	240
22	G4M	Gen 4 Energy	USA	LMR	25
23	SMR-160 (HI-SMUR)	Holtec Intl.	USA	PWR	160
24	mPower	Babcock & Wilcox	USA	iPWR	180
25	NuScale	NuScale Power	USA	iPWR	45
26	PRISM	GEH	USA	LMR	155

2.1 – Overview of the different technologies

Light water SMRs come in one of two varieties: conventional and integral ones. The former are merely scaled-down versions of Gigawatt-scale LWRs. The latter adopt the same operational principles as PWRs, except that the components of the nuclear steam supply system (NSSS) – containing the core, steam generator, pressurizer, and associated plumbing – are integrated into one vessel. The core is made up of rods similar to those found in large LWRs, only fewer and shorter, and sits towards the bottom of the vessel. Fission reactions in the core heat the water that, as in a conventional PWR, remains in a liquid state, forcing it through natural convection to flow upwards past an SG integrated into the vessel. When the water finishes interacting with the secondary loop in the SG, convection forces it to sink back to the bottom of the vessel, and the cycle repeats.

In an integral light water SMR, the vessel is not an RPV, but a “module” that incorporates all of the nuclear-grade equipment one typically finds in a conventional PWR’s containment building, as illustrated in figure 4 below. Since the NSSS is integrated into one vessel in this manner, the SMR is referred to as an “integral” PWR (iPWR). Because the approach to mitigating risks can be changed in such reactors by using features conventional reactors cannot exploit, they are arguably a distinct technology.

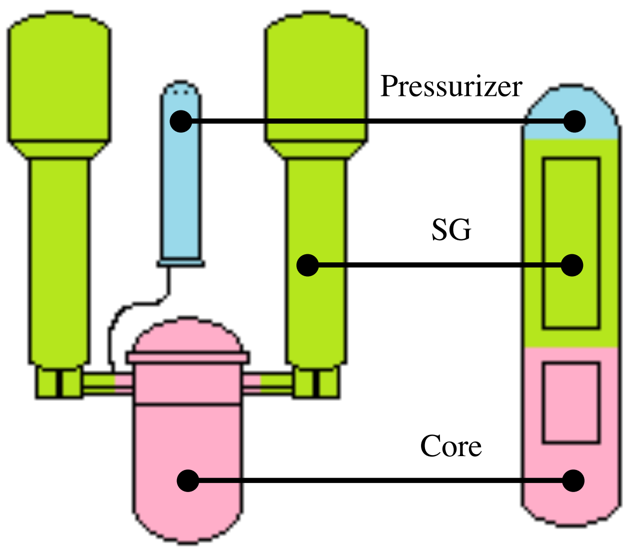
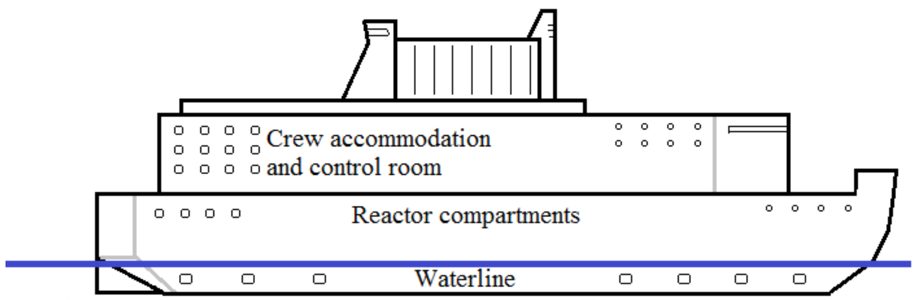


Figure 4. Compare the nuclear steam supply system of the 1,150MW$_e$, Gen III+ Westinghouse AP1000 (left) to that of the (now-shelved) 225MW$_e$ Westinghouse SMR (right). The NSSS is integrated into one module in an iPWR. The height of the AP1000’s RPV is 40ft (12m), whereas the height of the SMR module is 81 ft (25m).

Of the 26 proposed designs listed in table 1, 16 are LWRs. Of these, six are integral PWRs: they are being developed in Argentina (1), China (1), Korea (1), Russia (1), and the United States (2). Conventional light water SMRs are being developed in Brazil, China, France, Russia, and the United States. While the technology used to develop conventional light water SMRs is not new, their main "innovation" is their smaller size, which developers hope will result in lower total capital expenditure. In some cases, the smaller size facilitates secondary innovations in civilian NPP construction, mainly with regard to changing the deployment scenario, as figure 5 illustrates. The KLT-40S, for instance, is small enough for two units to be placed on a ship to create a floating nuclear power plant (FNPP) (27), while Flexblue's reactor will be housed in a submersible vessel (28). In both cases, the vessels will be anchored off the coast and the electricity transmitted on-shore to customers.



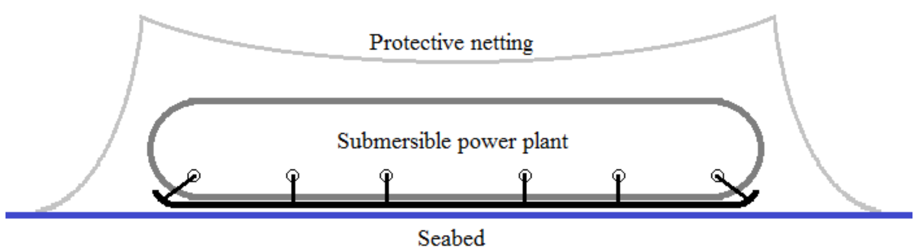


Figure 5. Smaller nuclear reactors can be deployed in ways that are infeasible for large reactors, such as underground, on a barge, or underwater. The KLT-40S FNPP (top) can be anchored off a customer's coast, while the Flexblue reactor (bottom) will be contained in a submersible vessel.

Ten non-light water SMRs are also listed in table 1. Two of these, both Indian designs (originally Canadian), are heavy water reactors. HWRs differ from LWRs in several respects. They use heavy water (D_2O) as both moderator and coolant, and their fuel is natural uranium dioxide. This means that the front-end of the fuel cycle is much simpler, as there is no need for expensive, technically complicated, and politically sensitive fuel enrichment facilities. All of the major components in an HWR are similar to those found in an LWR, except for the reactor core. Instead of an RPV loaded with fuel assemblies, HWRs have a large tank called a calandria that is penetrated by many pressurized horizontal tubes filled with pellets containing the natural uranium fuel. This setup is responsible for one of the remarkable features of HWRs: the ability to refuel the reactor while it is on-line (29).

The first of the two HWRs in table 1 is the PHWR-220, which is rated at $220MW_e$. This reactor is the workhorse of the Indian nuclear power industry, with 15 units in operation. The first of these was commissioned in 1980 in Rajasthan, while the most recent one was commissioned in 2011 in Kaiga (30). The second one of these, the AHWR-300LEU, is a $300MW_e$ experimental advanced heavy water reactor that is designed to burn a wider range of fuels, including thorium. It only uses heavy water as a moderator; its coolant is light water (31). A schematic diagram of the NSSS of a generic HWR can be seen in figure 6.

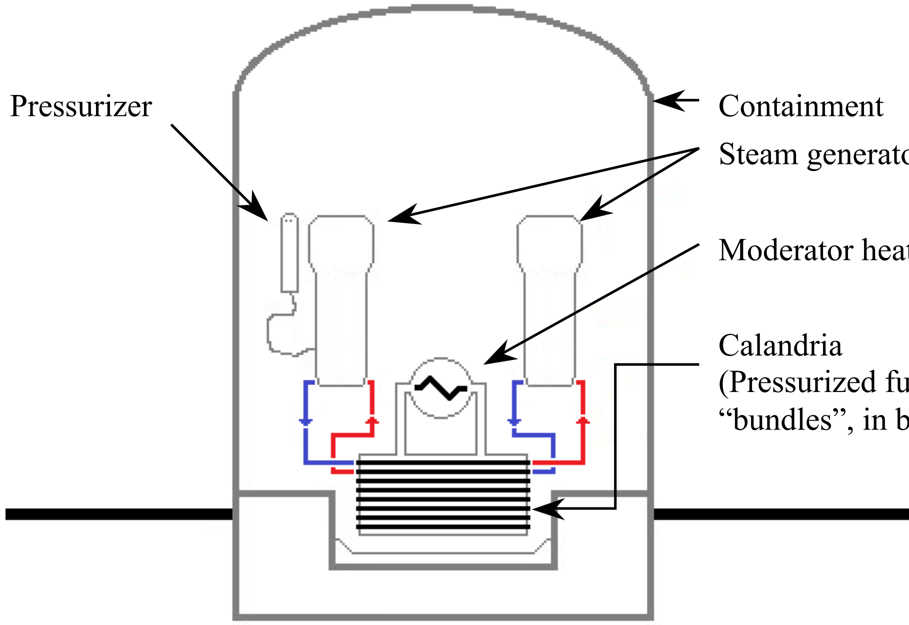


Figure 6. A schematic diagram of the NSSS of a heavy water reactor.

Another two designs in table 1 are high temperature reactors. These reactors are sometimes referred to as very high temperature reactors (VHTRs), gas cooled reactors (GCRs), or high temperature gas cooled reactors (HTGRs). These reactors use gas as opposed to water to cool the core; some use gas to run the turbine as well, thus employing a “full gas cycle.” The nuclear fuel in an HTR can either be in the form of pebbles that recirculate through the core, or in the form of fuel assemblies. Figure 7 presents schematic diagrams of the NSSSs of generic reactors of both types.

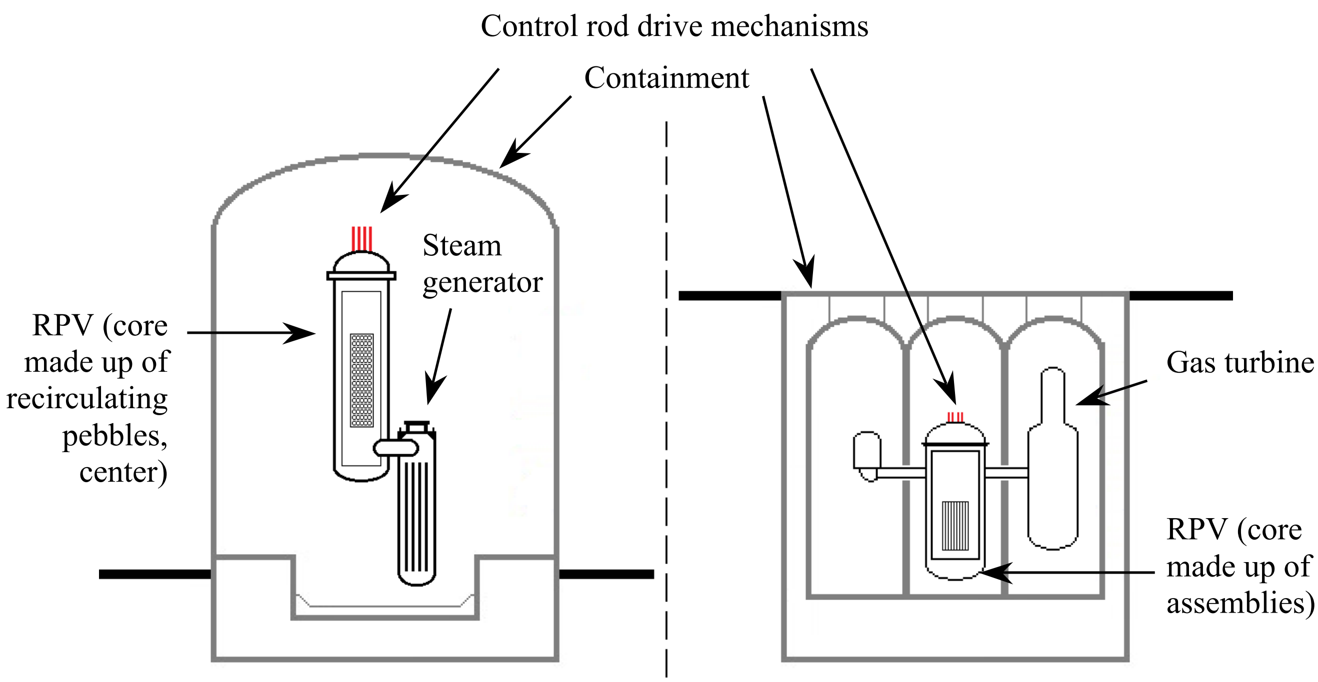


Figure 7. Schematic diagrams of the NSSSs of high temperature reactors that utilize a pebble-bed fuel arrangement (left, the HTR-PM) and fuel assemblies (right, the EM^2). Both of these reactors are listed in table 1.

One of the two HTR SMR designs, the HTR-PM, is a 105MW$_e$ pebble bed reactor. This reactor is fueled with kernels of UO_2 – each half a millimeter in diameter – that are enriched to 8.5% ^{235}U and covered with four layers of three isotropic materials, including pyrolytic carbon and silicon carbide. These particles, called tristructural-isotropic (TRISO) particles, are then scattered in a tennis ball-sized graphite pebble. The pebbles recirculate through the core of the reactor multiple times, heating up the helium coolant, which in turn heats up the water in the secondary loop powering the turbine (32). The construction of a full-size HTR-PM pilot plant is currently underway near the Chinese city of Rongcheng (33).

The reactors mentioned above moderate (reduce) the speed of the neutrons emitted during the nuclear fission reaction, either through water or graphite. The purpose of this moderation is to increase the nuclear cross section, or the probability that a nuclear fission reaction would occur, which permits the use of uranium fuel that is enriched to a relatively low level. In physics, to moderate a neutron is to “thermalize” it; hence, these reactors are referred to as thermal reactors (34, 35). Some reactor types, such as the ones discussed below, forego the moderator entirely, thus relying on “fast” neutrons. Because the nuclear cross section is lower when the neutrons are unmoderated, these “fast” reactors necessarily require fuel that is enriched to higher levels than would be found in thermal reactors.

The second HTR design is General Atomic’s 265MW$_e$ Energy Multipler Module (EM^2), the core of which is composed of assemblies containing processed spent fuel. This reactor employs a full helium cycle, with a gas turbine in place of a steam one.

The six LMR designs in table 1 are fast reactors that use fuel enriched up to 20% ^{235}U. They are called LMRs because they use liquid metal as their coolant: common options include molten sodium, molten lead, and a lead-bismuth eutectic mixture. Figure 8 presents a schematic diagram of the NSSS of a generic liquid metal reactor.

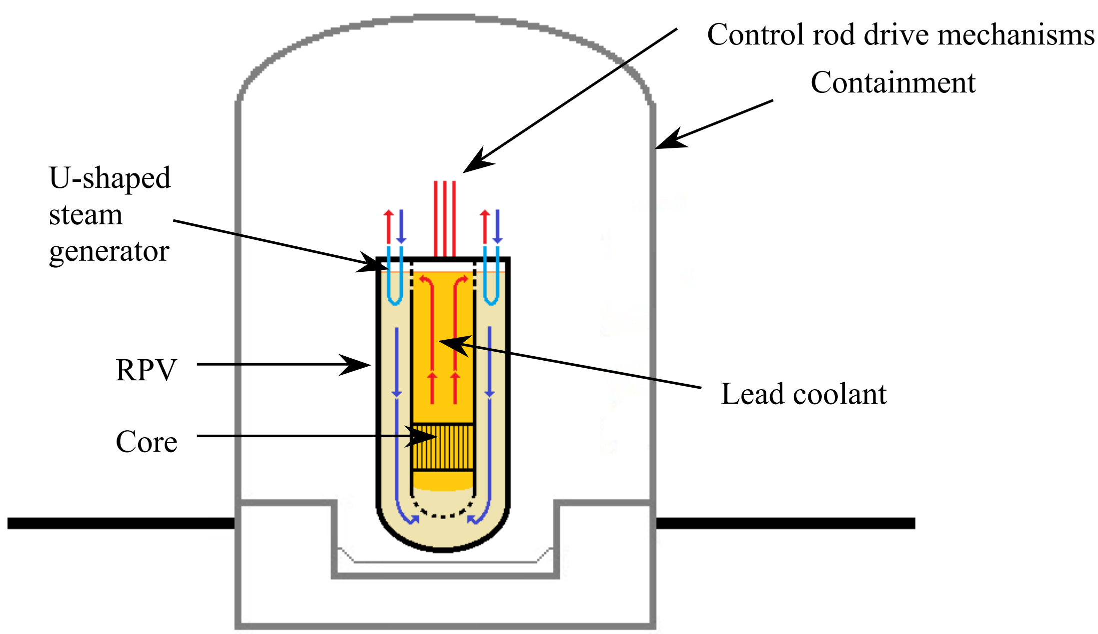


Figure 8. A schematic diagram of the NSSS of a liquid metal reactor.

The debate as to whether one of these technologies is more "technically sound" for the purpose of nuclear power production is as vociferous as it is futile. Each technology has its advantages and disadvantages, and the proponents of each are relentless in their attempts to prove that their technology is superior, either when it comes to safety, or proliferation resistance, or waste composition.

2.2 – Potential advantages and disadvantages of SMRs

The technologies presented in section 2.1 are not unique to SMRs; indeed, plans for large reactors of each type have been proposed, or even constructed and operated (36). This section will present those characteristics that proponents believe, if realized, make SMRs superior to large ones. In some cases, SMR-specific innovations that are considered advantageous by the technology's supporters come with their own problems.

For SMRs to become cost-effective and play a significant role in decarbonizing the world's energy system, they will need to be deployed in large numbers globally – certainly in the hundreds, but more likely in the thousands (37). If SMRs follow the historical trajectory set by large nuclear reactors, it is virtually impossible that they will achieve this level of success. The challenge facing SMRs is thus threefold: first, to change the construction paradigm; second, to change the deployment paradigm; and third, to change the institutional paradigm. We will highlight the potential advantages and disadvantages of SMRs as we discuss these three challenges.

Changing the construction paradigm:

Conventional nuclear reactors are built one-at-a-time, mostly on site, using specialized equipment and specially fabricated components. A vision that makes SMRs especially attractive is the possibility that they could be fabricated on an assembly line and shipped to a site ready to be plugged into the balance of plant. A key goal is to exploit economies of mass production and factory fabrication that have thus far eluded the nuclear industry, while reducing the amount of nuclear safety-grade construction on-site. This would make it possible to achieve much higher levels of quality control, since that would be done in the factory. Serial production would also help vendors incorporate technical improvements more quickly if nuclear construction were confined to one site. Incorporating passive safety features in the nuclear module could perhaps eliminate some of the plumbing associated with large plants. The benefits of fewer components are attractive for obvious reasons (38).

Controlling cost and construction duration are not the only benefits that might be realized with serial production. It should also be able to sustain a healthy supply chain. Building larger reactors entails ordering larger components, which squeezes all but the most financially capable component vendors out of the market (9–11). This allows those component vendors that remain to command a premium, raising the expenditure required for project execution. SMRs might strengthen the nuclear supply chain in two important ways: first, their smaller size means that more component vendors will be able to manufacture the components necessary for a nuclear reactor; second, their serial fabrication will guarantee an “order book” for components. Both of these factors might expand the nuclear supply chain.

Of course, harnessing economies of volume at the expense of economies of scale in reactor size also has its disadvantages. The cost per unit of power output might end up higher than that of conventional reactors: construction-related or regulation-induced overhead costs are not likely to scale with size. Moreover, if an SMR design is deployed in large quantities, and a manufacturing defect is discovered after such deployment, the technical, economic, social, and legal implications of removing or performing field modifications to many power plants might outweigh those caused by recalls in other businesses, such as the computer, automobile, and aircraft industries.

Plans for building a factory that would manufacture SMRs are strikingly absent from most discussions of SMR viability: either a large order book or investment by a sovereign state will likely be required to accomplish this task. No SMR vendor has yet been guaranteed either.

Finally, some have articulated a vision of delivering fully fueled reactors to a site and then, when the fuel is spent, retrieving the entire reactor vessel intact, so that no fueling or refueling occurs in the field. While attractive as a concept, for at least the next several decades it is highly unlikely that this will be possible, especially for the LWR designs that will be first into the market. We discuss this point in greater detail in chapter 6.

Changing the deployment and institutional paradigms:

Their smaller size allows SMRs to be deployed in ways and locations that would be infeasible for large reactors. Many SMR vendors envision installing their reactors in underground concrete vaults, immersed in water (e.g. 39). In the previous section, examples of floating SMR plants and submersible ones were introduced as well (27, 28). Vendors argue that such novel deployment strategies are designed to enhance safety and security. Most SMR designs aim to extend the refueling period beyond the 18 months of continuous operation that large reactors enjoy: some are developing reactors that require no on-site refueling over their entire lifetime (26, 40). Some vendors wish to "seal" their reactor as best they can: reducing the number of times the reactor can be accessed over its lifetime might enhance safety and security. At least one proposes sealing the module entirely such that it is delivered to the site with fresh fuel and removed from the site at end-of-life with its spent fuel intact (26). These efforts aim to prevent tampering with the fuel, which reduces the burden on plant operators and international inspectors, while handicapping potential terrorists. As noted previously, achieving this presents formidable challenges and, if it happens at all, is unlikely to occur for several decades.

Another aim is to prove to regulators that SMRs should entail lower safety and planning costs, with some vendors promising to reduce or abolish the need for an emergency planning zone (EPZ) around individual plants (41). Since SMRs have smaller radionuclide inventories than large reactors, the consequences of an accident involving an SMR are potentially smaller than those involving a large reactor. These factors, coupled with the elimination of large-diameter high pressure piping, current-generation passive safety measures, large emergency water inventories, and the reduction or abolition of a plant's reliance on operator intervention and off-site power, make adoption of the same safety measures for both SMRs and large reactors "almost certainly unjustifiable" (42).

Many vendors have also designed their plants for multi-reactor deployment (e.g. 39, 43, 44), with up to 12 reactors located on a site in one case (39). The incremental addition of units might make constructing reactors economically viable for utilities that cannot afford a large plant, or for poorer nations that nonetheless foresee greater energy consumption in the future (38). Thanks to their small size, SMRs will not tax water resources as much as large plants do, with one vendor designing a dry air-cooling system that makes its SMR viable in water-poor locations (44). SMRs may hold the potential to tap into a larger market, one where large plants are not an option due to challenging geographies, low demand requirements, or transmission grid constraints.

The ultimate goal is to prove that these reactors are flexible enough to deploy in areas where large reactors cannot be: either closer to population centers, in water-poor or grid-constrained locales, in regions with challenging geographies, in nations that do not have the institutional capacity to build a civilian nuclear industry the traditional way, or by operators that simply cannot afford the total capital expenditure that large reactors entail.

The reason deployment and institutional challenges were coupled in the discussion above must, by now, be obvious. It is precisely the greater flexibility afforded by SMRs that makes the need for new institutional arrangements imperative. In existing nuclear energy states, the regulation of these modules, and especially of multi-module plants, raises questions that have yet to be resolved; in the United States, the U.S. NRC has refrained from settling many issues until design certification applications are submitted (45). These include the size of the EPZ and the type of construction-operation interface they believe will be required during multi-module construction, among others. The resolution of most issues will have financial implications for vendors and for potential operators. Existing LWR-centric frameworks could potentially be adapted to cater to light water SMRs, though even this is not straightforward: eliminating or drastically reducing the EPZ requirement is a prime example (46). Moreover, questions surrounding operator training and maintenance culture will figure prominently if SMRs proliferate, unless vendors deliver reactors that require no operators, no maintenance crews, and no security staff, which is impossible. Finally, SMRs must address the concerns leveled against nuclear power in general, especially those of waste management and the perception of nuclear power as inherently dangerous (47, 48). Most light water designs call for the on-site management of waste, and passive safety features remain unproven on a commercial scale.

In emerging nuclear energy states, the challenge raised by the deployment of SMRs includes not only the set of issues raised above, but also questions of institutional capacity: exporting SMRs to nations that lack transparent, accountable, and independent institutions to safeguard nuclear facilities and respond to disasters will pose risks. The resolution of this issue is necessary for SMRs to succeed, given the importance of the international market to the SMR strategic business case (49).

Regardless of where they are deployed, a world more reliant on nuclear reactors will have to upgrade the fuel extraction, processing, and fabrication end of the cycle. It will also have to resolve the nuclear waste question. And, with a larger number of nuclear plants, it will have to enhance the international nuclear governance regime by demanding uncompromising security arrangements on the part of operators, by providing international inspectors with greater resources to do their job, and by formulating credible plans to manage incidents when they do occur.

Chapter 3: Investigating the capital costs of light water small modular reactors

From the UK's Walter Marshall to India's Homi Bhabha and America's Lewis Strauss, clean, low cost nuclear power has long been promoted as a key contributor to future human well being. Originally destined to provide energy "too cheap to meter" (a term Strauss used to describe the promise of fusion power, only for it to be co-opted by the nuclear industry and its supporters), the reality has turned out to be considerably different from Strauss' now-infamous words, and far more complicated (50–53).

The nuclear industry has struggled to prove that its reactors are economically competitive with other forms of electricity generation. The history of NPP construction is one of cost overruns and construction delays. SMRs could well prove to be more affordable than large reactors given their smaller size, but the affordability does not imply economic competitiveness: customers will always compare the cost of purchasing SMRs to that of other generators. And the emphasis on *capital* costs in the case of nuclear power stems from the facts that: "construction costs make up a large fraction of the total cost of nuclear power" (54); their operating cost as a proportion of total cost is low given the high energy density of the fuel; and the dearth of recent construction experience renders the estimates more uncertain and the projects financially riskier.

A somewhat modified version of this chapter was first published in the *Proceedings of the National Academy of Sciences* as:

Abdulla A, Azevedo IL and Morgan MG (2013) Expert assessments of the cost of light water small modular reactors. *Proc. Natl Acad. Sci.* 110(24):9686–9691.

3.1 – Brief history of nuclear power economics

In its 1962 Report to the President, the U.S. Atomic Energy Commission (AEC) suggested that nuclear power was on the cusp of a revolution that would see it made competitive with conventional forms of electricity generation (55). The two U.S. reactor vendors at the time, Westinghouse and General Electric, buoyed by such optimism and desperate to capture a potentially lucrative market, promised to deliver entire nuclear plant projects at a fixed price. These contracts were called 'turnkey' contracts – "all the electric utility had to do was 'open the door' of its complete plant… and start the generating equipment" (56). The costs the vendors promised were based on "expectation and not accomplishment," (57) and the actual costs turned out to be significantly higher than envisioned. Fewer than a dozen turnkey contracts were signed, with the vendors losing money as a result of these.

In 1965, American utilities began to place orders for reactors without firm price guarantees. Utilities and their ratepayers, not vendors, now shouldered the risk of cost overruns. Because of the promises made earlier that decade, the desire to gain experience operating nuclear power stations, and the fear of being left behind by the competition, nuclear operators placed even more orders in the latter half of the decade. In fact, "more than 80%" of all U.S. utility plant orders by the end of 1967 "were placed in 1966-1967" (58). The term applied to these two years is the "Great Bandwagon Market", a period when U.S. utilities enthusiastically placed "firm orders for 49 plants, totaling 39,732MW$_e$ of capacity," resulting in "intense competition… among the four reactor manufacturers" in the United States: Westinghouse, General Electric, Babcock & Wilcox, and Combustion Engineering (57).

These plants take a long time to build: they have "long lead times." Therefore, the only real cost data customers had access to (in terms of accomplishment) when placing orders during the "Great Bandwagon Market" was that of the first generation of plants. These reactors were very different from the reactors the vendors were marketing in the late 1960s. As Bupp and Derien so bluntly put it, well into the 1970s,

> "many lost sight of the fact that it was not becoming easier to answer a simple but important question: 'How much does a light water plant cost?'… Even though more than 100 light water reactors were under construction or in operation in the United States by the end of 1975, their capital cost was almost anyone's guess" (58).

Actual costs turned out to be vastly greater than those estimated prior to construction start: the average overrun in overnight costs (i.e. the cost of constructing the plant minus financing charges) for builds initiated in 1967 and 1968 was more than 100%. Later projects, despite more conservative estimates from utilities, saw even greater cost overruns. The overrun for builds initiated in 1968 and 1969 averaged almost 200%, while those initiated in the first half of the 1970s averaged more than 250% (59). There is a long history of cost estimates for conventional reactors that have turned out to be in serious error (60). Figure 9 below compares the estimated cost of nuclear plants prior to construction with their actual cost (61).

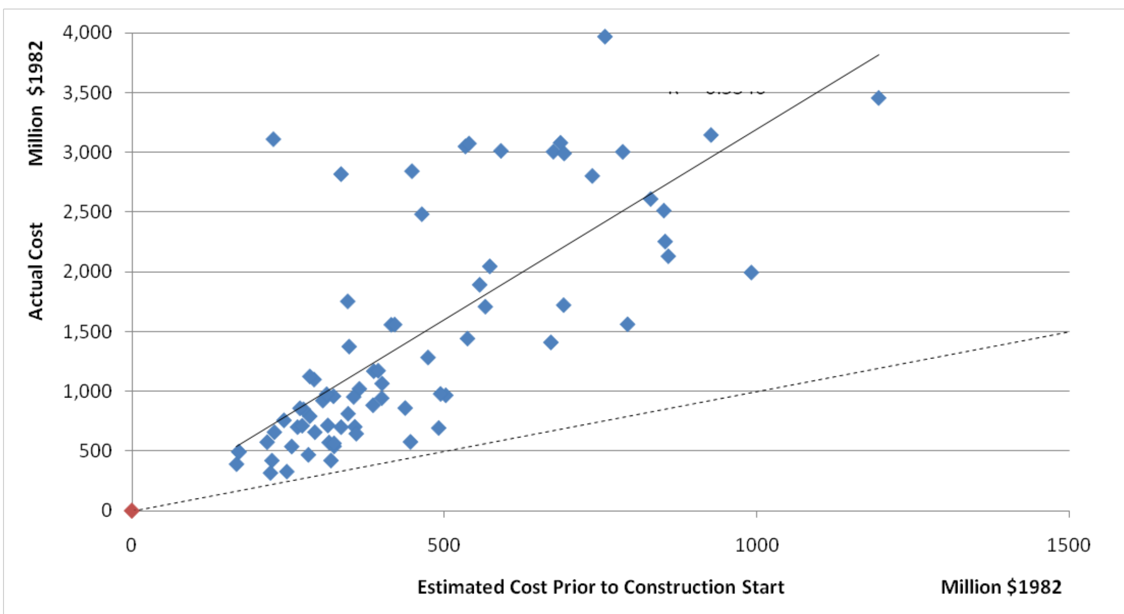


Figure 9. Nuclear power has a record of poor and optimistic cost estimation. As this plot by Talabi and Fischbeck (61) shows, in some cases, actual costs turned out to be many times greater than the cost estimates made prior to construction. The solid line is a linear fit of the data, while the dotted one is the 1:1 actual cost to estimated cost line.

This problem was not limited to American plants. Starting in the 1970s, France, acknowledging both the economic challenges posed by large NPPs and its great reliance on nuclear power, and partly for cost control, sought a national industrial policy that standardized NPP construction and operation to a greater extent than any other country. This one-vendor, one-design (per order batch), one-operator, one-regulator approach was nuclear power's best chance at achieving economic competitiveness through cost control, quality assurance, and learning-by-doing. And yet, assessment of recently released data from the French nuclear industry shows how the French nuclear scale-up, "legitimately considered the most successful scaling-up of a complex, large-scale technology in the recent history of industrialized countries" (62), also saw remarkable cost overruns, prompting its designation as "a case of negative learning by doing" (62).

During the Great Bandwagon Market of the late 1960s, the lack of standardization and design completion prior to construction start surely did not help control costs, though the French experience shows that this is not sufficient to explain away the cost overruns. One culprit was the industry's drive to harness economies of scale in reactor output. The size of the units kept increasing. This was done less for the sake of improving plant design or safety and more for the sake of improving plant economics by vendors that had just sustained large losses on nine turnkey bids. The competition to build ever larger plants reached such proportions that, "by 1968, manufacturers were taking orders for plants six times larger than the largest one then in operation" (63).

Although some manufacturers "suspected that size extrapolations would create problems, they had no way to prove their fears" (64). As the regulatory framework matured, and as incidents at nuclear plants began to occur, those reactors that were under construction kept incorporating state-of-the-art safety systems to diminish abnormal plant operation, which added to their capital costs. Needless to say, each of these new, bigger reactors became a first-of-a-kind

(FOAK) project with its own set of technical, economic, and regulatory hurdles. Of course, there were other factors, both within the nuclear industry and outside it, that led to poor economic performance in the 1960s. For example, this time period also saw an oil glut as large oil and gas discoveries were made worldwide and production ramped in many corners of the world, including the Middle East, the Soviet Union, and Canada (65). This made it harder for NPPs to compete with alternative generation technologies.

3.2 – Approaches to cost-estimation

Individuals, companies and other organizations, as well as governments, must make important decisions in the face of considerable uncertainty. While we gather what evidence we can – as individuals we choose where to go to college, who to marry, and whether to have children – we do this all in the face of at least some irreducible uncertainty. Similarly, companies choose to invest in major new technologies, and governments adopt tax and research and development policies, without knowing for certain how their decisions will play out.

Sometimes research can yield better understanding and data, but it is rare that all uncertainty can be eliminated. This is especially true in decisions about whether to make multi-billion dollar investments in the development of a new technology. In most such cases, some uncertainty will remain until the technology has actually been developed and implemented. Even then, it may take several iterations before a complex new technology can be gotten on a downward-sloping learning curve (66) so that costs decrease with its increased adoption.

At the outset, to help them reach the most informed decision possible, analysts and policy makers frequently want estimates of the cost and performance of such technologies, and perhaps even of how they are likely to evolve across different factors, such as investment costs, operation and maintenance costs, technical performance, and public acceptability, among others. In this chapter, our focus is on assessing the future capital costs of nuclear power, in particular, of integral light water SMRs. Several methods can be employed to shed light on the issue of SMR capital cost. These include (1) running regression or econometric methods that use historical data to generate estimates; (2) employing scaling factors from technologies where costs are known, 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 to generate such estimates 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 evolves 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) the sample size of nuclear power plants is rather low and (2) as mentioned in the previous section, the "technology" studied is nowhere near a consistent design (i.e. each plant arguably sits on a different cost curve), mean that the results are both variable and generate little insight to guide estimates of future costs of nuclear plants. We present a few such examples here. In their 2001 study, McDonald and Schrattenholzer (67) report learning rates for a number of energy technologies, including NPPs. They estimate that the learning rate of nuclear power in the developed world – those countries that belong to the Organization for Economic Co-operation and Development (OECD) – from 1975 to 1993 was about 6%; Using existing data on the American nuclear industry, as well as data on the French nuclear experience, Grubler (62) 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 has been a "negative learning by doing" effect: specific costs increase rather than decrease with accumulated experience. One could of course argue whether using the word "learning" in this context is appropriate. Grubler explicitly 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 (68) conducts a similar assessment of the costs of U.S. NPPs. In his work, nuclear power exhibits an increasing cost trend as a function of the cumulative capacity installed. 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 the SMRs we are investigating, the business case for which is predicated on the assumption that they will be factory-fabricated, unlike legacy nuclear plants. A more fundamental point is that this strategy is indefensible in cases where one wants to assess the costs of new, emergent technology for which there are no historical data, again, like SMRs.

Another strategy is to estimate the cost of a new technology by applying a scaling factor to an existing benchmark. One popular way of doing this for SMRs is to estimate their future costs by using the reported costs of large-scale nuclear reactors as a starting point, "scaling" the costs by size (MW_e capacity). Kuzentsov and Barkatullah, acknowledging the fact that SMR cost estimates in 2009 may be mere conjecture, explicitly adopt this approach (69). 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. (38) provide a good example of this approach.

Another 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 (70). 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 here, is a top-down expert elicitation, an approach to generating estimates that we elaborate on in section 3.3 below. 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 does this.

3.3 – The use of expert elicitation to assess the capital costs of light water SMRs

Our brains are not well equipped to make decisions that involve considerable uncertainty. As extensive empirical research has now shown, we make such judgments using a variety of cognitive heuristics that, while they serve us adequately in many day-to-day settings, can result in overconfidence and bias that leads both lay people and experts astray when they address more complex and unusual problems (71, 72). Decision science (73–77) offers a set of strategies for improving how we make important decisions in the face of uncertainty.

In addressing such decisions, one should start with the best scientific, technical, and analytical evidence that is available. But, because such formal evidence often does not capture the full extent of what experts know, in addition to seeking informal expert advice, it is common in decision science to employ formal methods to obtain systematic probabilistic judgments from experts who are intimately familiar with the current state of knowledge (78–80). For example, such methods have been used to characterize uncertainty about climate science (81, 82), the impacts of climate change (83–85), and the heath impacts of environmental pollutants (86, 87). Of course, the same cognitive limitations that arise when we try to make unaided decisions also arise when experts attempt to provide probabilistic judgments (72). Too often when seeking expert advice, little or nothing is done to limit overconfidence and reduce bias. Ubiquitous overconfidence (79) and the biases arising from cognitive heuristics such as availability and anchoring and adjustment (71, 88–90) cannot be completely eliminated. However, well-designed expert elicitations can use a variety of strategies to help improve the quality of expert judgments (78–80).

Expert elicitation about emerging energy technologies that is deeply informed by careful technical analysis is still relatively rare (91). Here we report the results of applying these methods to integral light water SMRs. 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.

While there are few detailed economic analyses of these designs in the public literature, results from top-down approaches to SMR cost estimations (e.g. 69) are problematic because the designs of these SMRs are sufficiently different from their larger cousins to place them on a very different cost curve. The few studies employing a bottom-up approach decompose an SMR into major constituent components (many of which have yet to be fabricated) and build up a total capital cost estimate using a combination of authors' judgments and consultation with component vendors (e.g. 92). At the early stages of design development, even these bottom-up approaches may be performed relative to a benchmark such as a large reactor design.

In an effort to improve on these past estimates, and better assess the associated uncertainty, we designed and ran an expert elicitation which: 1) specified the details of two light water SMR designs, including their major sub-components, at substantial length; 2) made careful systematic efforts to control for and address the cognitive heuristics that can lead to bias and overconfidence; and, 3) as they responded to our questions, asked experts who are directly or indirectly engaged in light water SMR design to carefully consider all available evidence (which in most cases implicitly included the bottom-up engineering-economic analysis that they, or their organizations, are conducting).

We conducted sixteen face-to-face interviews with experts drawn from, or closely associated with, the nuclear industry. Twelve of the experts were employed by major U.S. reactor vendors that were actively developing commercial SMRs at the time. Three were contractors to those firms and one was a National Laboratory scientist familiar with the proposed designs. Table 2 provides a summary of expert demographics and areas of expertise.

Table 2. A summary of the demographics of the experts who took part in our study.

Summary information:	
Number of experts	16
Number of organizations represented	4
Years spent in the nuclear industry (this includes experience working in both military and civilian programs):	
Cumulative	> 450
Average	28
Standard deviation	14
Years spent in management (including project management):	
Cumulative	> 320
Average	22
Standard deviation	14
Number of experts whose current position falls in the following areas (there was no limit on the number of areas of experience an expert could report, so several selected multiple areas):	
Auditing / Financial / Accounting	2
Government relations / Marketing / Public relations	5
Human resources / Legal	2
Technical services / Operations / Research and development	10
Management / Project management	10
Supply chain development / Supply chain logistics	4

As detailed in appendix A, we developed descriptions of two integral light water SMR designs. Because most of our experts were actively involved in commercial SMR development, we were careful to base our questions on publicly available blueprints of these reactors and not ask for design-specific data that might compromise proprietary vendor information. While we did not ask them to reveal company proprietary details, most were able to draw upon their detailed design knowledge in answering our questions. The specifications we developed for the first SMR (160 MW_{th}, 45 MW_e) were based on descriptions from NuScale (93). Specifications for the second SMR (800 MW_{th}, 225 MW_e) were similarly based on publicly available descriptions from the then-active Westinghouse SMR effort (94).

We developed five deployment scenarios. Scenario 1 involved a 1,000MW_e Generation III+ (i.e. a current-generation) reactor. Scenario 2 involved a single 45MW_e light water SMR plant, while scenario 3 involved five of these SMRs co-sited to form a 225MW_e complex. Twenty-four 45MW_e SMRs were co-sited to form a Gigawatt-scale (1,080MW_e) facility in Scenario 4. Finally, scenario 5 involved a single 225MW_e unit.

The elicitation focused on assessing the “overnight capital cost” of each of the five scenarios. We were careful to define this term as the sum of engineering, procurement, and construction (EPC) costs. It excluded site-work, transmission upgrades and other "owner's costs." In short, we asked for an estimate of the lump sum payment (reported in 2012 dollars) that a customer would transfer to a vendor to acquire an nth-of-a-kind (NOAK) plant, excluding the cost of financing. At NOAK, it is assumed that the vendor has recouped the cost of design engineering and licensing, has exploited technological learning, and has streamlined construction management. In addition, we asked for estimates of the probability of NOAK cost hitting certain (arbitrary) targets. This gave us two ways of constructing cumulative distribution functions (CDFs) of anticipated SMR capital cost.

In developing the five scenarios we were careful to specify that the plants were being built under a “favorable” regulatory environment, overseen by a regulator such as the U.S. Nuclear Regulatory Commission (NRC). We asked the experts to assume that no significant deviations from current U.S. regulatory practice had occurred (for example, no major change in how waste is managed), that the regulator had deemed the SMR deployment scenarios acceptable, and that the owner had already licensed the plant. We suggested the southeastern U.S. as the candidate location for the plants.

Many organizations have Codes of Account that provide a line-item description of each component or system required for the successful completion of any project. In order to gain an understanding of the relative cost contribution of different elements in each plant, we bundled the elements of the IAEA Code of Accounts for Nuclear Power Plants (95) into twelve categories (building and site preparation; reactor plant equipment; turbine plant equipment; etc.) so that, for a subset of twelve of our sixteen experts, we were able to elicit judgments about the relative contribution of each category to overall cost. Because the IAEA Code of Accounts was developed for conventional designs, we also had experts assess the relevance of each of these categories for SMRs.

We also asked experts to sketch the construction schedules for our hypothetical designs and sought specific insight about how, if at all, the deployment of multiple SMRs on one site might influence cost. We elicited detailed views about global deployment options. Finally, we sought judgments about features that might contribute to the relative economic attractiveness and the safety and security of light water SMRs. The interview closed with an expert-led, open-ended discussion of the benefits of and challenges to deploying these new reactors.

In the months leading up to the interviews, we engaged in several rounds of discussion, each of which resulted in the iterative expansion of certain areas of inquiry, their exclusion, or the refinement of the questions.

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 these valuable 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 social science researchers 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.

Attempts to systematically address pitfalls like overconfidence mainly involved (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 outlined by Morgan and Henrion (79), where readers can find a more comprehensive treatment.

Our elicitation process began by assessing bounds. Assume an expert provided a lower bound estimate for the capital cost of a scenario when prompted. We then asked him to explain why he though that number was correct (regardless of what it was). If an expert provided a lower bound of \$3,000 per kW_e, for example, he or she was asked why it could not be lower than that. The purpose of this prompting exercise was to expand the universe of alternatives that the expert was considering. If this process was repeated for the upper bound, and the expert revised his estimate both times, then he had effectively considered a more complete universe of alternatives than he previously had, which meant his revised range was less overconfident than his original range. The expert might stick to his original range after prompting from the interviewer, which is 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. The interviewer elicited the median, or "best," estimate last; this was done to avoid the expert anchoring on a certain number.

The second method we used to avoid overconfidence involved 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 was allowing us to construct a CDF that we could then compare to the probabilistic judgments he provided in response to the first question. If the two CDFs generated two different pictures of capital cost, the inconsistency was brought to the expert's attention, and he was asked to revise his estimates.

The above discussion demonstrates the importance of developing a well-specified system for the elicitation, hence our emphasis on the technical depth that goes 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.

3.4 – Expert assessments of the cost of light water small modular reactors

We elicited estimates of the overnight cost of each scenario in dollars per kilowatt-electric ($\$/kW_e$). We report these estimates in figure 10A. Median estimates of the overnight cost of a 1,000MW_e current-generation reactor – scenario 1 – range from \$2,600 to \$6,600 per kW_e (90% confidence intervals range from \$1,000 to \$10,000 per kW_e). Given the history of cost overruns and construction delays for large reactors, discussed in section 3.1, it is not surprising that median estimates of the overnight cost of a new Gen III+ plant vary by more than a factor of 2.5. Indeed, given the past history, the fact that thirteen of the sixteen experts provide median estimates that lie between \$4,100/kW_e and \$6,100/kW_e might even be viewed as a sign of persistent overconfidence in the industry. Median estimates for scenario 2, a single-unit 45MW_e light water SMR, range from \$4,000 to \$16,300 per kW_e (90% confidence intervals range from \$2,000 to \$25,500 per kW_e), while those for a single-unit 225MW_e SMR (scenario 5) range from \$3,200 to \$7,100 per kW_e (90% confidence intervals range from \$1,800 to \$12,200 per kW_e).

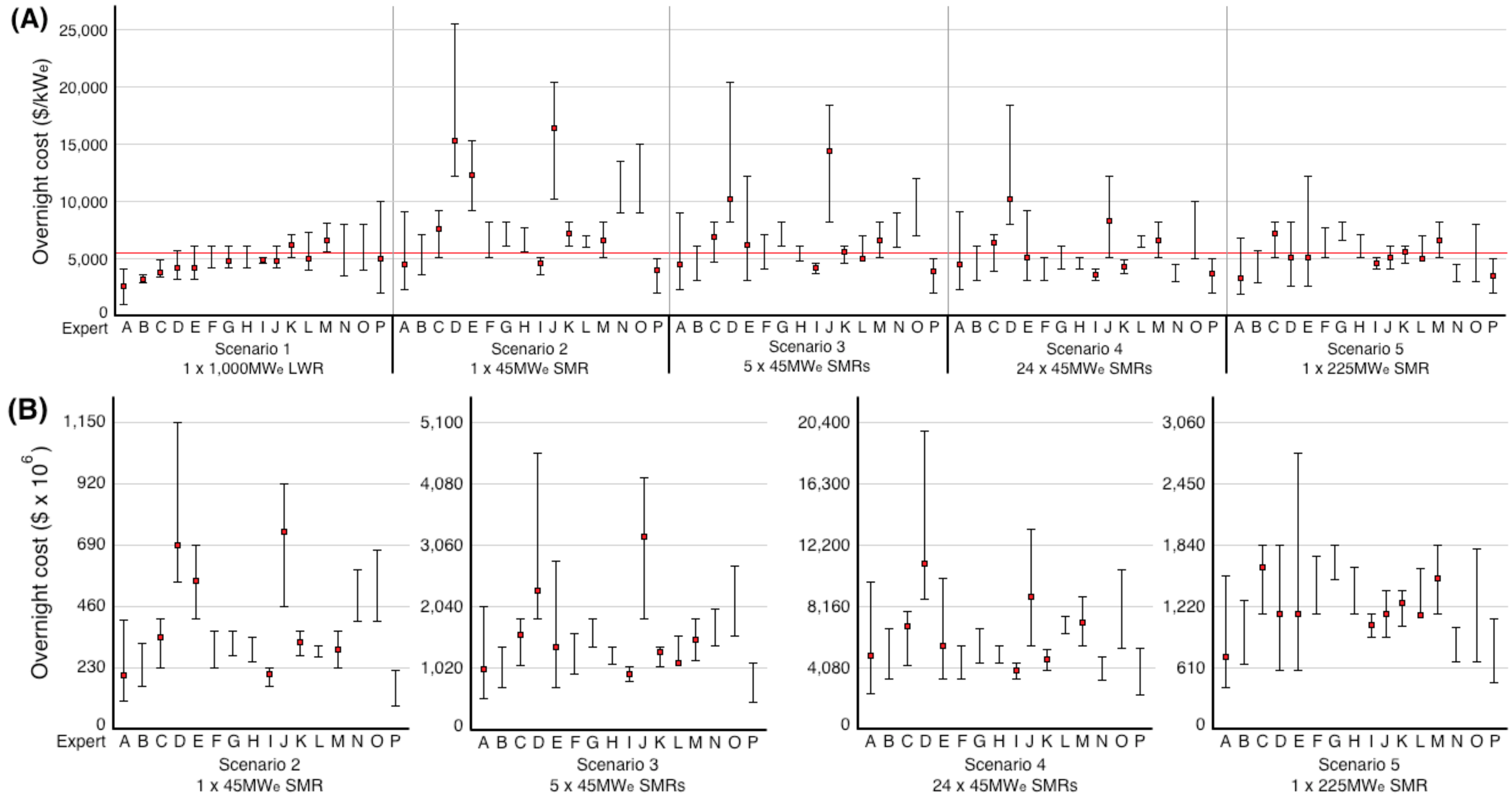


Figure 10. Estimates of overnight cost elicited from sixteen nuclear power experts for each of five nuclear reactor deployment scenarios. A) Each expert (A through P) provided estimates of the overnight cost per kilowatt of reactor capacity for each scenario. The details of the scenarios are noted on the horizontal axis. The solid line represents the Energy Information Administration's 2011 estimate of the overnight cost of a dual-unit large LWR plant (96). B) For the four SMR-plant configurations, each of the estimates in (A) is multiplied by plant capacity to arrive at project cost. Expert M's estimate included owner's cost (costs that fall out of the vendor's scope, such as site work, transmission upgrades, etc.).

We asked our experts to estimate construction times for each of the three basic designs. There was consensus that construction would follow a traditional s-curve (slow start, then more rapid progress, slower completion). On average, our experts believed that an NOAK 1,000MW$_e$ Gen III+ plant would take five years from first concrete to commissioning (table 3). There was consensus that light water SMRs could probably be built in three rather than five years, due to the increased use of modular construction, the integration of all nuclear components into a single factory-built module, and the reduced complexity of the balance of plant.

Table 3. Fourteen experts' estimates of construction duration in months for each of the single-unit plants. This was defined as the period from the pouring of first safety concrete to plant commissioning and delivery of the first kilowatt-hour. Experts C and M did not respond to this question.

Expert	1,000MW$_e$ Gen III+ LWR plant	45MW$_e$ SMR plant	225MW$_e$ SMR plant
A	72	36	48
B	42	18	24
D	60	42	30
E	60	36	48
F	60	36	36
G	72	36	48
H	48	36	36
I	60	24	30
J	66	54	48
K	54	30	36
L	54	36	36
N	60	24	36
O	48	36	36
P	48	24	36
Mean	**57**	**33**	**38**

Almost all of the experts argued that the smaller a reactor becomes, the greater the diseconomies of scale in the cost of pressure vessel and similar components. Experts' estimates of overnight cost for a single 45MW$_e$ unit (scenario 2) break into two groups. Eleven experts gave median costs between 4,000 \$/kW$_e$ and 7,700 \$/kW$_e$ (the average was 5,800 \$/kW$_e$), with

90% confidence intervals ranging from a low of 2,000 $/kW$_e$ to a high of 9,200 $/kW$_e$. However, five experts (D, E, J, N, and O) provided estimates that lie as much as a factor of two to three higher. These experts also assessed much wider uncertainty bounds (a low of 9,000 $/kW$_e$ to a high of 25,500 $/kW$_e$). These five experts argued that costs rise rapidly as reactors become smaller, with the result that the 45MW$_e$ reactor is especially disadvantaged. The four of these five who worked for nuclear technology vendors claimed that finding a "sweet spot" that would allow for an economically viable but small reactor is a difficult exercise that is on-going even as they proceed in their detailed designs.

When we moved to consider five 45MW$_e$ units on a single site (scenario 3), several experts were skeptical about whether such deployment strategies would be allowed since, under existing NRC regulations (97), one cannot operate more than two reactors from a single control room. Experts D, E, and I all expressed such doubts but were nevertheless willing to make cost estimates. For example, expert I said, "I don't think this is doable… but you're asking me to assume [that the] NRC has signed off on it. Okay, if that's the case, this is how I'd build it."

While the rate of cost reduction varied, all but two experts believed that, if locating multiple units on a single site were allowed, it would reduce unit capital costs. This is because site-specific lessons learned during the installation of the first module can be applied to later units (figure 11). For the case of five 45MW$_e$ reactors on the same site, experts E, N, and O reduced their cost estimates to levels and ranges similar to those of the others. In doing this they argued that the move to several hundred MW$_e$ would allow developers to exploit economies of scale in the supply chain and the cost-saving benefits of shared systems. Expert D reduced his median cost estimate by a third, but – despite the detailed information in our scenario – believed that he needed to retain his wide confidence interval because so much remains unknown about actual deployment, from the construction-operation interface to the number and type of safety systems required to manage multi-module plants that share certain systems. Expert J did not believe that there would be significant cost advantages to co-locating a modest number of SMRs. Note however, that when the number of co-located reactors was increased to twenty-four, even this expert believed that some cost advantage could be achieved if many SMRs could be co-located. In figure 10B we multiply elicited costs by plant capacity for each scenario to arrive at estimates of "project" cost in 2012 dollars. Expert E, J and O anticipate large (≥ 2x) benefits for this case. Experts A and M argued that any savings would be canceled out by the increased regulatory constraints on managing a site with several reactors in proximity.

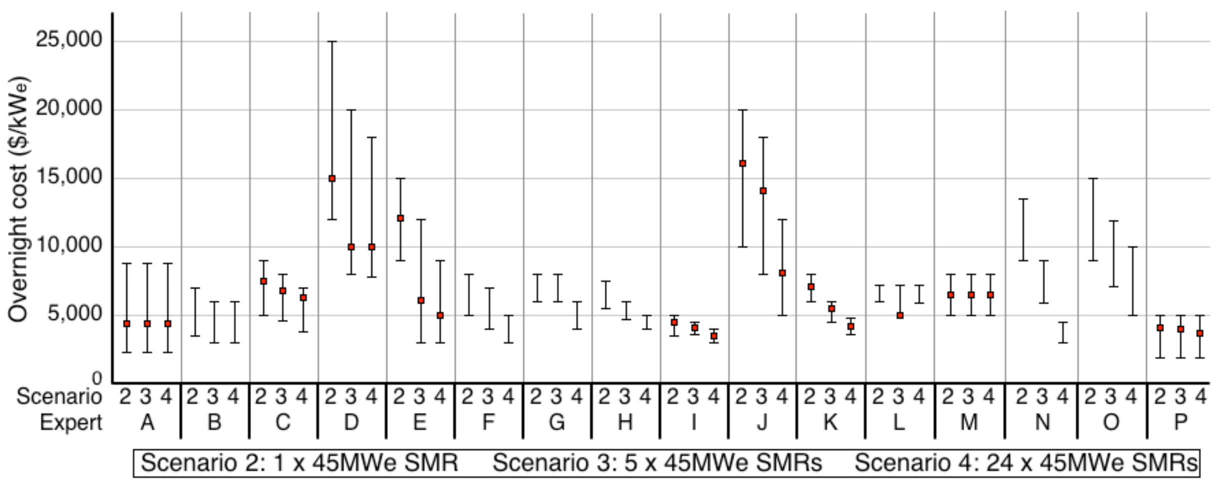


Figure 11. Most experts believed there would be learning from co-siting. Scenarios 2, 3, and 4 entailed 1, 5, and 24 45MW$_e$ SMRs deployed on a single site, respectively, to create nuclear installations of different capacities. Co-siting reactors may decrease a plant's overnight cost per kilowatt. These economies may be exploited by allowing for extensive use of shared systems. However, experts emphasized the importance of resolving safety questions before this occurs. Expert M's estimate included owner's cost.

In addition to asking for the cost of multiple co-sited 45MW$_e$ reactors, we also asked the experts to sketch experience curves that expressed the relationship between the number of modules installed at a facility and the cost of deploying an additional unit at that site for both of our SMR designs. Six experts did not have time or did not feel they could respond in those terms.

Of the ten who did respond, the breakdown of the twenty rates provided (each of the ten experts judged each of the two SMR designs) was as follows: three gave rates of zero to 1% (i.e. essentially no learning), nine gave rates of 10% (i.e., the costs decline by 10% with each doubling of installed capacity), three gave rates between 10 and 15%, and one gave a range from 10 to 20%. While some experts suggested that the smaller SMR, designed for multi-module deployment, might yield higher learning rates, the results do not seem to favor one design over the other. Experts generally agreed that there has been little discussion of the intricate operating procedures that would be required to build such multi-reactor facilities, and that deployment scenarios must be carefully studied at the design certification stage and executed well at the construction stage.

We challenged experts to identify potential economies of scale in modular construction and the economies of volume associated with factory fabrication that might be exploited in smaller reactors (38). Without prompting from us, Expert I suggested that a greater number of off-the-shelf components would compensate for diseconomies of scale in reactor size. When asked, a few others reluctantly conceded this point, admitting that the potential for such economies must be explored, especially those associated with the supply chain: everything from drafting the purchase orders, to fabricating, shipping, and installing these smaller components should be easier if one could guarantee that a customer will buy twenty-four. However, most experts were skeptical that such economies would completely offset the diseconomies of scale in reactor size.

There was disagreement about whether co-siting five 45MW_e SMRs would cost less than building a stand-alone 225MW_e SMR. Seven experts believed the complexity of the multi-module plant would lead to higher capital costs than the stand-alone plant. Five believed the reverse, citing the benefits of economies of volume that favor the plant that is designed for greater flexibility and co-siting. Four (experts K, L, M, and P) judged the cost of the two deployment options to be similar.

Proponents of SMRs emphasize that they may solve many problems beside project cost and construction duration. We asked experts for their judgment as to the value of a set of these benefits accrued from various sources in the literature (25, 38, 49, 69, 92–94, 98–100). Results are reported in figure 12A. Factory fabrication is ranked as holding the largest potential for improvement; followed by reduced construction time, design simplicity and flexibility in siting options.

There was little consensus as to whether the regulatory environment in the U.S. will be amenable to accommodating SMR deployment scenarios that involve: multi-module plant construction; siting SMR plants close to population centers; or exporting SMRs to countries with little or no experience operating nuclear plants.

(A)

	Of no value			Of some value			Of utmost value
Factory fabrication of reactor and NSSS					4	4	7
Shorter construction schedules	1		1	1.5	2.5	5	4
Inherent simplicity of design		1	1	1	3.5	5	3.5
More flexible siting options		1	2	2	1	5	3
Elimination of skeletal construction		1		2	5	4	3
More flexible sizing options	1	3		4	2	3	2
Alternative end-use options	1	2.5	2	2	3.5	2.5	1.5
Different safety and planning costs	1	3	1	3	3	2.5	1.5
Different decommissioning costs	2.5	3.5		7	1	1	

(B)

	Of no concern			Of as much concern as conventional reactors			Of utmost concern
Large-break loss-of-coolant accidents	4	7	2	2			
Small-break loss-of-coolant accidents		9.5	3.5	2			
Loss of off-site power		6	4	5			
Extreme, low-probability events		2	7	4	1		
Spent fuel stockpile management		2		11	1		1
Common mode failures			4	8	3		
Active sabotage (including proliferation)		2	2	7	3	1	
Reactor design		1	3	7.5	3.5		
Maintenance culture		1	1	9	2	2	
Adequacy of regulatory framework			1	6	4	3	
Operator training culture			1	11	2	1	

Figure 12. Expert valuation of promised SMR economic and safety advantages. A) Opinions regarding the value of SMR-specific economic and safety advantages were elicited from each expert. The darker a box is, the larger the number of experts who checked it; the number of experts who checked each box is also shown. B) Opinions regarding the safety and security challenges faced by SMRs relative to large reactors were elicited in a manner similar to (A) above.

In order to determine which cost and risk factors are alleviated by SMRs, we asked experts to assess relevant issues on a seven-point scale (figure 12B). The risks of loss-of-coolant accidents and loss-of-offsite-power were judged to be lower for SMRs relative to conventional plants. This is to be expected since the elimination of large-diameter plumbing makes the risk of a large-break loss-of-coolant accident much lower, and passive safety systems are designed to reduce dependence on off-site power and operator intervention. Most experts raised the question of spent fuel management but, in terms of proliferation risk, our experts believed that light water SMRs do not change the technology's current security paradigm.

Reporting all the arguments experts advanced in a 2-3 hour interview in not feasible. Here, we have tried to convey a sense of the dialogue that we had with experts and highlighted the sources of uncertainty discussed most by our experts.

In figure 13, we compare our results with estimates from the literature derived using some of the methods outlined in section 3.2 above. Notice the tight band within which most estimates fall. Estimates are adjusted to 2012 dollars using the consumer price index (CPI).

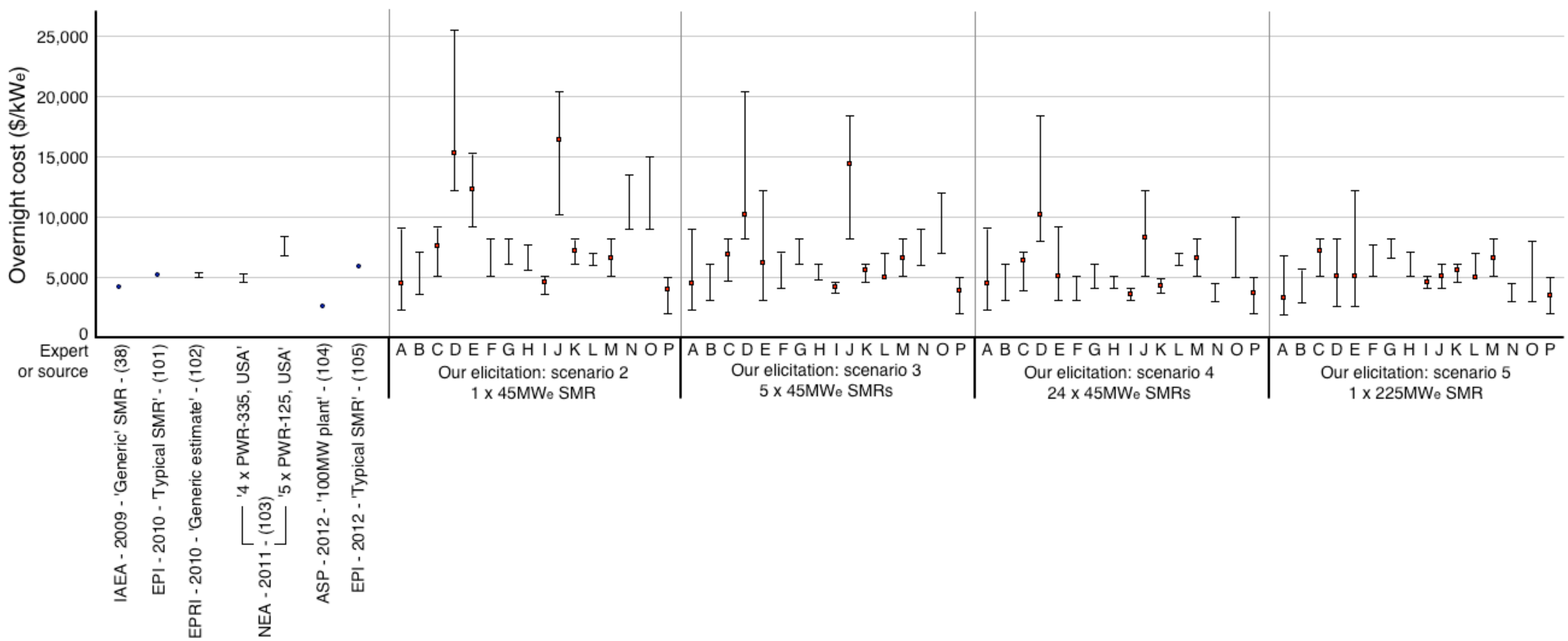


Figure 13. A comparison of our elicitation results with existing estimates of SMR cost, the sources of which are listed in the figure. Estimates were adjusted for inflation and, like our results, presented in 2012 dollars.

At this stage of such a complex technology's development, this suggests that most of these estimates were either 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.

3.5 – Conclusions derived from this study

Uncertainty about capital cost is a key factor in the debate over whether, how soon, and to what extent SMRs will play a significant role in future energy systems. While our results provide an improved understanding of this factor, there are obviously other factors that affect the viability of SMRs as an energy source. These include questions about the nature of the future regulatory environment, and about safety, spent fuel management, operating cost, the speed with which the transition will occur from FOAK plants to NOAK plants, and the amount of learning that will occur over the course of this transition. The answers will depend on, and be inter-related with, the size of domestic and international markets that develop. At this stage of the technology's development, many of these questions are unanswerable, nor are the technical experts we interviewed in a position to offer informed judgments about most such matters.

Results from our expert elicitations provide quantitative support for four important insights about SMRs. First, while the vision of dramatic cost reduction through factory mass production remains appealing, and may yet be realized with the development of future advanced designs, the lower bounds on our experts' cost estimates suggest strongly that this vision will *not* be achieved by the light water SMRs that will be available on the market over the next few decades.

Second, even if we adopt our experts' upper bound estimates of overnight cost for single-unit SMRs, it seems likely that a single SMR unit will cost considerably less in absolute terms than the several billion dollars required for large Gen III+ nuclear plants. In locations where public attitudes will allow SMRs to be built, the biggest factor in the decision to construct a plant may shift from the customer's ability to finance the project to a careful consideration of opportunity cost. As reducing CO_2 emissions becomes more important, an SMR's smaller size may also open markets outside of the electricity industry. The promise of SMRs may also grow as the limitations of integrating variable and intermittent renewable power into systems become more widely appreciated. In the future, both lower up-front cost and new markets could yield a more attractive economic paradigm for SMR vendors.

Third, even when considerable detail is provided about the technical design and regulatory environment that plausibly may apply for first-generation SMRs, experts who are intimately involved in their design have highly diverse views about what they will cost when sited under a range of scenarios. To some extent this uncertainty might have been anticipated qualitatively from published point estimates. However, as figure 13 indicates, most prior point estimates are on the low side of the cost ranges several of our experts assessed. The two that report uncertainty, report *much* tighter ranges. Our results make the disagreement, and even the uncertainty in the estimates by individual experts, much more explicit. The results identify some of the key uncertainties that vendor engineers believe must be resolved before more robust cost assessments can be made. This should prove useful for research decision makers and other relevant stakeholders.

Finally, results from this chapter can be used directly as inputs in stochastic simulation models that are designed to explore the likely evolution of the energy system over the next several decades, and to assess the cost and timing of meeting a variety of low carbon energy targets.

Chapter 4: Exploring the economic viability of light water small reactors

Another economic metric of interest when it comes to nuclear power is a plant's levelized cost of electricity (LCOE). The LCOE is the price the nuclear plant must charge per unit of electricity sold for it to break even over its lifetime.

Customers, policymakers, and energy analysts are interested in more than just nuclear power's capital costs. The LCOE is a more comprehensive measure that takes into account capital costs, both fixed and variable operating costs, decommissioning costs, the plant's construction duration, its lifetime, capacity factor, heat rate, and the cost of financing the project. Equation 1 below depicts one approach to computing the LCOE:

$$LCOE = \frac{\sum_{y=1}^{n}\left(\frac{I_y + OM_y}{(1+d)^y}\right)}{\sum_{y=1}^{n}\left(\frac{E_y}{(1+d)^y}\right)} \quad (1)$$

where

n	is plant lifetime
I_y	is the investment cost in year y (initial and incremental capital)
OM_y	is the operating and maintenance cost in year y (fixed and variable)
d	is the discount rate
E_y	is the electricity generated in year y

Another approach, described in detail for the case of concentrated solar power by Wagner and Rubin (106), is to compute the levelized annual cost (LAC) of a technology and divide that annual cost by the average annual electricity generated. These two methods – using equation 1 above or the approach used by Wagner and Rubin – give broadly similar results. For detailed commentary on methods of assessing the cost of electricity, please consult Kammen and Paca, 2004 (107).

This chapter has been submitted to *Energy Economics* for peer-review.

4.1 – Developing levelized cost estimates for light water small modular reactors

One investigation of nuclear power economics in the twenty-first century is MIT's *Future of Nuclear Power* (108). In this study, MIT constructed a cost schedule for a hypothetical Gigawatt-scale nuclear plant and, applying the procedure presented in equation 1, concluded that the LCOE from this plant would range from $42 to $67/MWh of electricity generated. The findings were released in 2003; these numbers are therefore in 2003 U.S. dollars. In 2009, a team from MIT updated the figures to take into account changes in the commodities market, as well as revised estimates of the cost of nuclear power plants, estimating a LCOE of $84/MWh in 2007 dollars (109). Although it is possible to criticize the structure of the cost schedule employed in these studies as too academic, the lack of experience with nuclear construction makes studies by academic groups important in the case of this technology.

We constructed a cost schedule based on the *Update on the Cost of Nuclear Power* and, after reproducing the results of that study, we used capital cost and construction duration estimates from the expert elicitation in chapter 3 to generate estimates of the LCOE of four of the five NPP deployment scenarios constructed for the elicitation. Characteristics of the four scenarios are summarized in table 4 below.

Table 4. Four hypothetical nuclear reactor deployment scenarios were presented to our experts.

	Number and type of reactors on the same site	Individual reactor capacity (MW_e)	Total plant capacity (MW_e)
Scenario 1	1 "typical" Gen III+ PWR	1,000	1,000
Scenario 2	1 light water SMR	45	45
Scenario 3	5 light water SMRs	45	225
Scenario 4	1 light water SMR	225	225

Table 5 below lists some of the parameters used in constructing the cost schedules. We retained some of the values used in the MIT study for the purpose of comparing our results to existing estimates. This is especially true where no better information on which to update the data existed. For our baseline scenario, we adopted a weighted average cost of capital (WACC) of 10%, a heat rate of 10,400 BTU/kWh, and a 37% tax rate – the same assumptions made in the MIT report (109). We change MIT's capacity factor from 85% to 90% and the lifetime of the plants from 40 to 60 years to reflect the fact that Gen III+ builds are designed to operate at these higher capacity factors and for this extended lifetime. The construction duration of the conventional reactor is modeled as a five-year schedule, with 10% of the construction performed in each of the first and fifth years, 25% of the construction completed in each of the second and fourth years, and 30% of the construction completed in year 3. This implies an S-shaped construction profile, as suggested by the experts we interviewed. The single-unit SMR plants take three years to build; the capital spent is spread out evenly among the years. The multi-module SMR plant (scenario 3 in table 4) takes five years to build; the capital is spread out evenly among the years. Again, this conforms to the consensus of the experts interviewed during the expert elicitation.

Table 5. Parameters used to calculate the LCOE for the scenarios under investigation.

Variable *(Units)*	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Capacity *(MW_e)*	1,000	45	225	225
Capacity factor *(%)*	90	90	90	90
Construction duration *(years)*	5	3	5	3
Heat rate *(BTU/kWh)*	10,400	10,400	10,400	10,400
Overnight cost *($/kWe)*	*Data derived from expert elicitations (table C1)*			
Incremental cap. Cost *($/kWe)*	*1% of overnight cost*			

Fixed O&M cost *($/kWe/year)*	61	61 – 122	61 – 122	61 – 122
Var. O&M cost *(mills/kWh)*	0.46	0.46 – 0.92	0.46 – 0.92	0.46 – 0.92
Fuel costs *($/mmBTU)*	0.68	0.68	0.68	0.68
Waste fee *($/kWh)*	0.001	0.001	0.001	0.001
Decommissioning costs *($)*	*Calculated from Code of Federal Regulations*			
O&M real escalation *(%)*	1	1	1	1
Fuel real escalation *(%)*	0.5	0.5	0.5	0.5
Tax rate *(%)*	37	37	37	37
WACC *(%)*	10	10	10	10
Lifetime *(years)*	60	60	60	60

The overnight capital costs were derived from each individual expert's distribution, and the incremental capital cost was calculated from the overnight cost. The resulting incremental capital cost figures, especially for the single-unit SMR plants, might be too low. However, SMR vendors promise that these designs will require less maintenance. In any event, absent more information about how reliable these will be, there exists no basis on which we can update MIT's estimates. Similarly, because we never asked for O&M cost estimates in our elicitation procedure, the values used in our model were updated versions of those used by MIT. The scaling was done using the CPI.

Rounding out our discussion of the remaining parameters in table 5, fuel costs were taken from the Nuclear Energy Institute's (NEI's) 2011 estimate of delivered nuclear fuel cost (110), the waste fee is set by statute, and the decommissioning costs were calculated using the Code of Federal Regulation's (CFR) current decommissioning funding allowance (DFA) requirements.

We used an application of equation 1 to compute an average cost of electricity, which is the ratio between the discounted after-tax cash flows (the numerator in equation 2 below) and the discounted energy output:

$$LCOE = \frac{\sum_{t=1}^{n+tconst}\left\{\left(A\left(C_t^{construction} - R_{tax} \times C_t^{depreciation}\right) + \left[(1-R_{tax}) \times \left(C_t^{o\&m}\right)\right]\right) \times \left[\frac{1}{(1+WACC)^t}\right]\right\}}{\sum_{t=1+tconst}^{n+tconst}\left\{\left(Output \times \left(1+R_{inf}\right)^t \times (1-R_{tax})\right) \times \left[\frac{1}{(1+WACC)^t}\right]\right\}} \qquad (2)$$

In equation 2, $WACC$ is the weighted average cost of capital; R_{inf} is the rate of inflation; R_{tax} is the expected rate of taxation; $Output$ (in kWh) is the annual electricity output, which is computed by multiplying the plant capacity S (in kW_e) by the capacity factor and by 8,760; and $C_t^{construction}$ is the construction cost in year t (in dollars per kW_e, and is a function of construction duration and schedule). Since different types of plants have different construction profiles, we included these explicitly in the LCOE estimate, as shown in table 5. While capital costs are incurred in the initial year, electricity generation only starts once the construction ends: t_{const} is the difference between the year in which construction begins and the first year the plant generates power. Thus, *n+tconst* is the last year of plant operation. $C_t^{depreciation}$ is the depreciation amount in year t (in dollars). Our depreciation schedule follows the Modified Accelerated Cost Recovery System (MACRS), as per IRS regulations for large power plant projects.

$C_t^{o\&m}$ is the cost of operating and maintaining the plant in year t (in dollars). This is composed of:

C_{icc}	Incremental capital cost (in dollars per kW_e per year)
C^{decomm}	Decommissioning cost (in dollars) when $t = n+tconst$

$C_{FIXo\&m}$	Fixed O&M cost (in dollars per kW_e per year)
$C_{VARo\&m}$	Variable O&M cost (in dollars per kWh)
C_{fuel}	Fuel cost (in dollars per mmBTU)
C_{waste}	Waste fee (in dollars per kWh)

All of these costs are subject to inflation and real cost escalations, except the waste fee, which is fixed by statute. Equation 3 below presents the components of the O&M cost variable:

$$
\begin{aligned}
C_t^{o\&m} = {} & \left(S \times C_{icc} + C_t^{decomm}\right) \times \left(1 + R_{inf}\right)^t \\
& + \left(S \times C_{FIXo\&m} + Output \times C_{VARo\&m}\right) \times \left[(1 + ESC_{o\&m})\left(1 + R_{inf}\right)\right]^t \\
& + \left(Output \times C_{waste}\right) + \left(Output \times HR \times C_{fuel}\right) \times \left[\left(1 + ESC_{fuel}\right)\left(1 + R_{inf}\right)\right]^t
\end{aligned} \tag{3}
$$

Three of the variables in equation 3 have yet to be defined. These are $ESC_{o\&m}$, which is the percentage of O&M cost real escalation; HR, which is the plant's heat rate (in BTU/kWh); and ESC_{fuel}, which is the percentage of fuel cost real escalation.

Figure 14 below shows the LCOE for the four scenarios, using the estimates of individual experts. All values are in 2012 dollars:

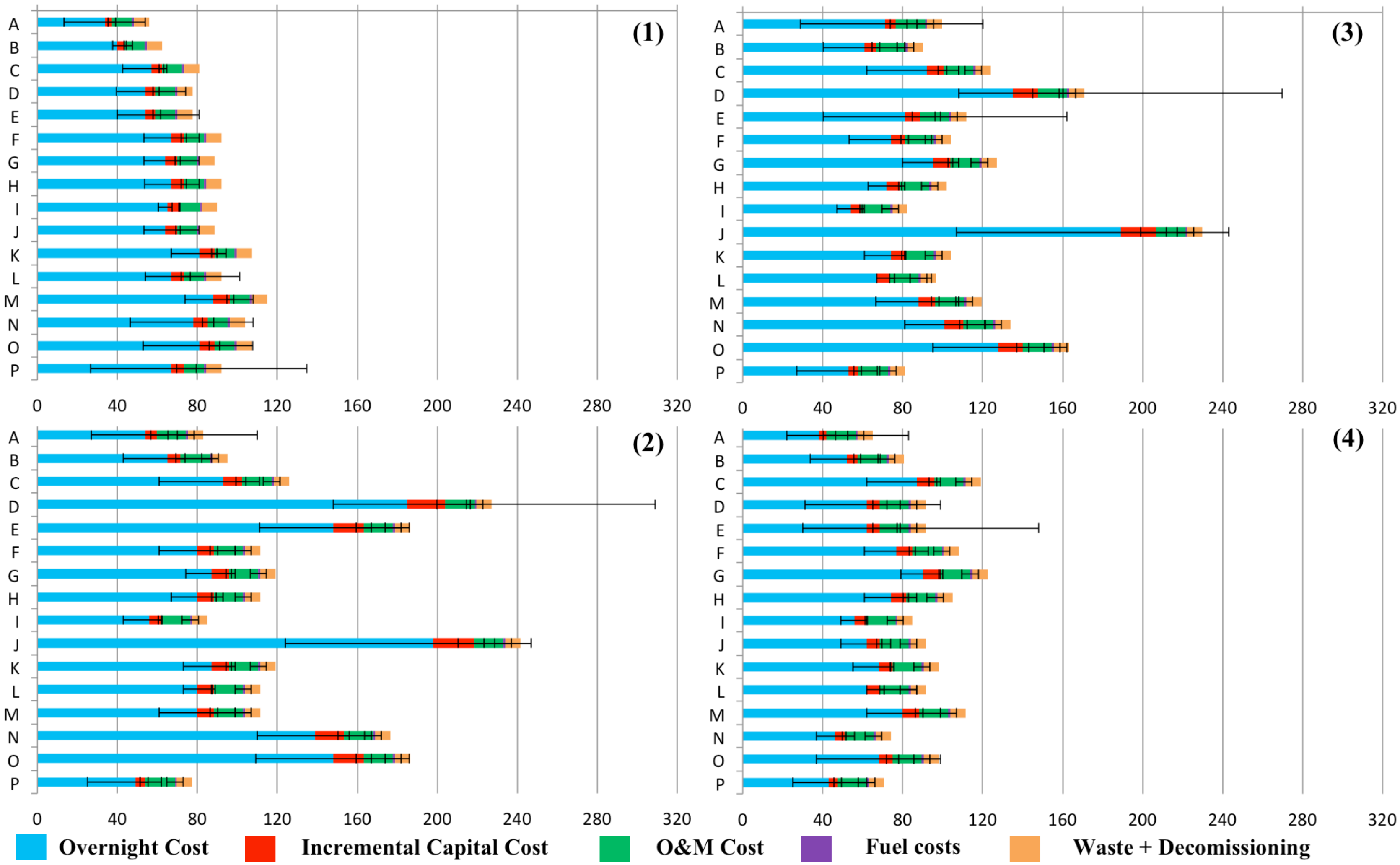


Figure 14. Using individual experts' overnight cost estimates, we calculate the LCOE in 2012 $/MWh of (1) a 1,000MW$_e$ Gen III+ reactor plant, (2) a 45MW$_e$ integral light water SMR plant, (3) a five-module 45MW$_e$ light water SMR plant, and (4) a 225 MW$_e$ light water SMR plant. WACC = 10%. Uncertainty ranges are provided for each sub-component of total system LCOE.

There is no consensus among our experts regarding the overnight cost of either the large reactor or the three SMR scenarios. Naturally, given nuclear power's intensive capital requirements, the estimates of levelized cost therefore span a wide range. For the large plant, median levelized cost estimates range from $56 to $120 per MWh. Five of the sixteen estimates (K, M, N, O, and P) suggest a median LCOE greater than $100 per MWh for the large reactor plant; only two (A and B) suggest an LCOE less than $80 per MWh. The capital intensiveness of nuclear power is clear from figure 14: levelized capital cost accounts for anywhere from around 60% to 80% of total system levelized cost in scenario 1. Eight of the sixteen experts have median overnight cost estimates within 10% of the median overnight cost estimate of the aggregated expert distributions for this scenario.

The wide range of SMR overnight cost estimates elicited from the experts leads to a wide range of levelized cost estimates for these scenarios too. Median estimates of system levelized cost range from $77 to $240 per MWh for scenario 2, with levelized capital cost again accounting for around 60% to 80% of system levelized cost. Twelve of the sixteen median estimates suggest a LCOE greater than $100 per MWh. Estimates of the median overnight cost vary considerably, with only one expert's median overnight cost estimate falling within 10% of the median overnight cost estimate of the aggregated expert distributions for this scenario. When co-locating five 45MW_e SMRs on one site (scenario 3), median estimates of total levelized cost range from $81 to $230 per MWh. Levelized capital cost accounts for around 65% to 80% of total system levelized cost in this scenario, and five of the sixteen experts' median overnight cost estimates fall within 10% of the median overnight cost estimate of the aggregated expert distributions for this scenario.

Although the overnight cost estimates of this scenario are generally lower than those of scenario 2, we assumed that it takes five years for the staggered construction of these five co-located units to be completed, compared with three years for scenario 2. Under current regulations, it is improbable that modules would be commissioned while adjacent modules remain under construction. Innovative construction-operation interfaces, if approved by the regulator, might change the economics of such deployments. Despite the longer construction duration, which leads to a delay in the initiation of the revenue stream, these units still have a LCOE lower than that of scenario 2, thanks to the economies of scale associated with the co-location of multiple modules on the same site, leading to lower overnight cost estimates in our experts' judgment.

The 225MW_e SMR in scenario 4 generates estimates of total system levelized cost that are lower than those of the other SMR scenarios, and only slightly higher than for the large reactor. Despite its shorter construction duration (three vs. five years), its higher overnight cost still puts it at a disadvantage relative to the large reactor. Median estimates for scenario 4's total system levelized cost range from $65 to $120 per MWh. Seven of the sixteen experts have median overnight cost estimates within 10% of the overnight cost estimate of the aggregated expert distributions for this scenario.

To generate one estimate for each reactor type, we aggregate the assessments of the sixteen experts, assigning equal weights to each. Table 6 summarizes our results:

Table 6. Range of LCOE estimates for the four nuclear power plant deployment scenarios, aggregating the judgments of sixteen experts, each of whom is assigned equal weight.

Scenario	Mean overnight cost *($/kWe)*	WACC; lifetime *(years)*	Levelized cost of energy *($/MWh)*		
			5^{th} perc.	50^{th} perc.	95^{th} perc.
1: 1 × 1,000MW_e	4,900	10%; 60	82	**91**	99
2: 1 × 45MW_e	8,500	10%; 60	123	**140**	160
3: 5 × 45 = 225MW_e	6,900	10%; 60	109	**125**	143
4: 1 × 225MW_e	5,300	10%; 60	85	**95**	106

The median LCOE estimate for the Gigawatt-scale reactor is $91 per MWh. The small SMR scenarios have a higher levelized cost. Locating one small (45MW_e) SMR on a site will yield an LCOE of $140 per MWh (median estimate), with the 90^{th} confidence interval ranging from $123 to $160 per MWh. Locating five small units on a site would be less expensive, owing to the lower overnight cost distribution. This despite the longer construction duration (five instead of three years) and the assumption that the plant can be commissioned only once all five units are in place. Again, scenario 4, a plant consisting of a single 225MW_e SMR, yields only a slightly higher LCOE estimate than the large reactor. Although its overnight cost is greater than the large plant, we assume that it is brought online two years faster than the large plant, generating a revenue stream sooner. The shorter construction schedule fails to neutralize the premium associated with the SMR's higher overnight cost.

We conducted a sensitivity analysis on these results to explore the effects of varying the WACC and the lifetime of the plants on total system levelized cost. Table 7 below shows that increasing the WACC increases the LCOE, as it makes the investment riskier. Decreasing the lifetime also increases the LCOE, because the reduced payback period demands a higher break-even cost. However, given how discounted the cash flows for years 41 and beyond are, the increase in LCOE is small. Ultimately, table 7 proves that LCOE is fundamentally less sensitive to lifetime than it is to the riskiness of the investment or, of course, to the overnight capital cost. There is precedence for this conclusion in the literature (54).

Table 7. Varying the WACC and plant lifetime to assess the sensitivity of the LCOE estimates to these two variables.

Scenario	Mean overnight cost *($/kWe)*	WACC; lifetime *(years)*	Levelized cost of energy *($/MWh)* 5th perc.	50th perc.	95th perc.
1: 1 × 1,000MW$_e$	4,900	10%; 60	82	**91**	99
		12%; 60	102	113	125
		10%; 40	85	94	103
2: 1 × 45MW$_e$	8,500	10%; 60	123	**140**	160
		12%; 60	151	172	199
		10%; 40	127	144	165
3: 5 × 45 = 225MW$_e$	6,900	10%; 60	109	**125**	143
		12%; 60	136	156	181
		10%; 40	114	129	149
4: 1 × 225MW$_e$	5,300	10%; 60	82	**95**	106
		12%; 60	103	116	130
		10%; 40	85	98	110

The total system levelized cost is not very sensitive to project lifetime, due to the heavily discounted cash flows in later years. As implied in section 4.1, this discounting in later years exposes the LCOE metric to allegations of short-termism. The performance of currently operating NPPs has been improving, in terms of both power uprates and capacity factor increases.

In figure 15, we compare the range of LCOEs generated in our analysis with the range of LCOEs reported by the Energy Information Administration (EIA) in its Annual Energy Outlook 2012 (111). It is important to note that the assumptions made in the calculation of these levelized costs can be somewhat different. For instance, carbon-intensive technologies are penalized by the EIA to the tune of an extra 3% in their capital cost values, which generates an impact “similar to that of an emissions fee of $15 per metric ton of carbon dioxide" (111). All technologies are deployed at utility-scale, and all values are converted to 2012 dollars.

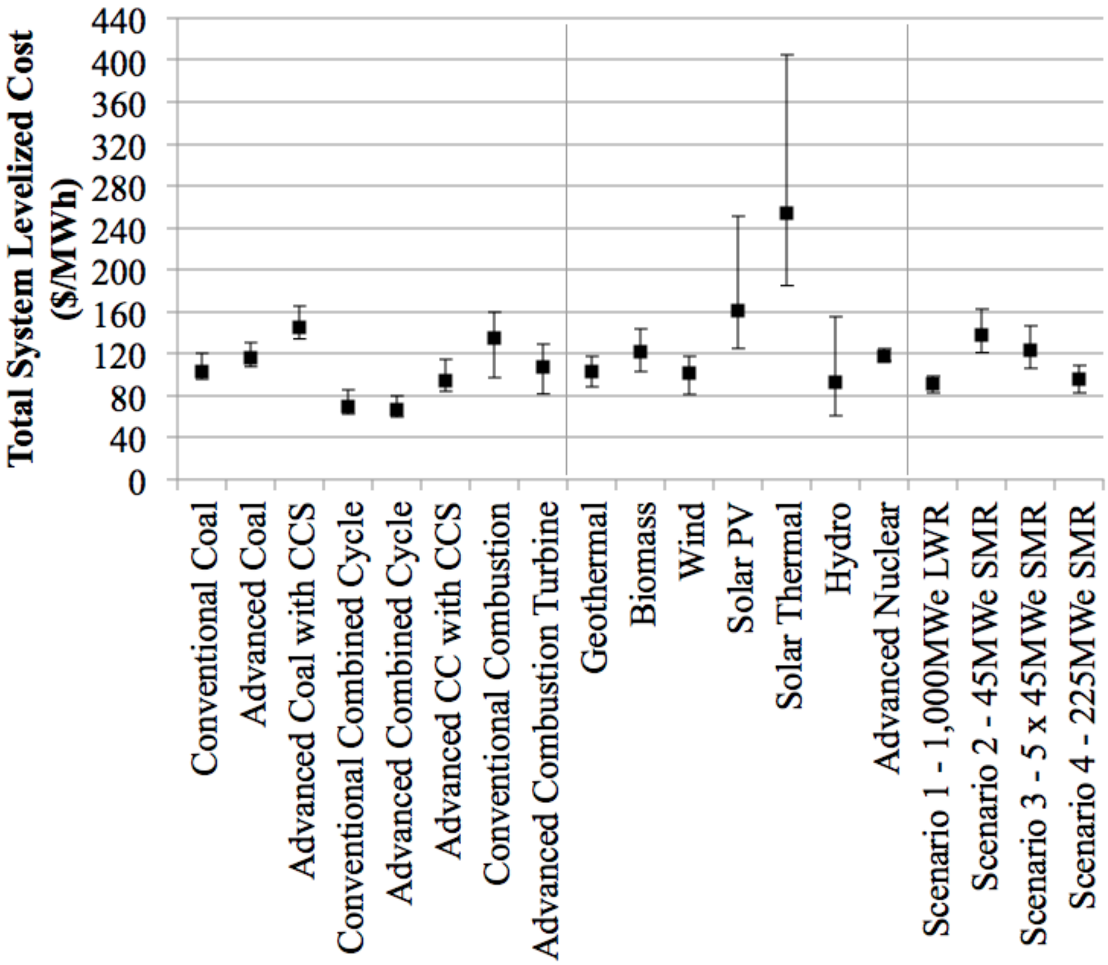


Figure 15. The levelized cost of electricity for various generators, as reported by the Energy Information Administration in its Annual Energy Outlook 2012 (113). Our four scenarios are included for comparative purposes.

The LCOE of all five nuclear plant scenarios is higher than that of basic natural gas deployment options. However, it is obvious that nuclear is more competitive with new coal, especially if carbon capture and sequestration (CCS) is mandated. Moreover, nuclear power appears to remain competitive with the renewable technologies analyzed by the EIA.

Figure 16 compares the distribution of total system levelized costs generated in this chapter with distributions of U.S. wholesale electricity prices in 2012 in nine trading hubs across the nation (112). All prices are in 2012 dollars. The distributions for the four plants represent the aggregate of expert assessments of overnight cost, along with the uncertainties in other LCOE parameters reported in table 5.

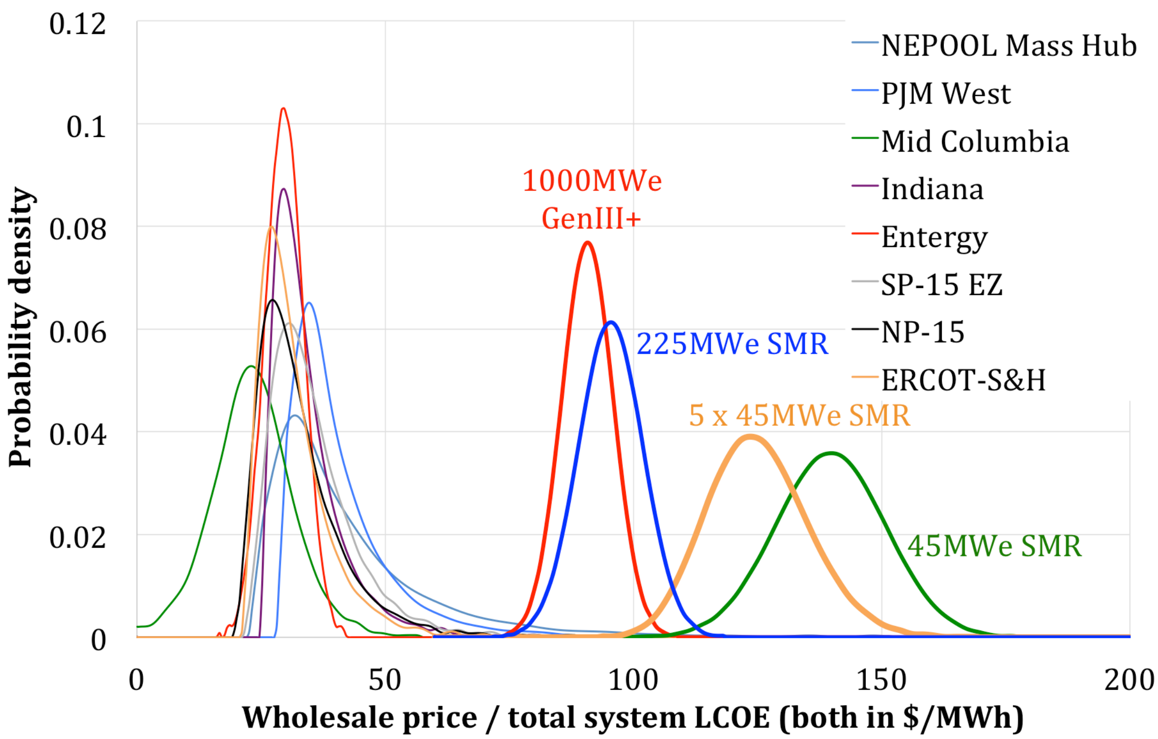


Figure 16. Comparing the distribution of total system levelized costs generated in this study with U.S. wholesale electricity prices in 2012 across nine trading hubs. Note that the prices in the two ERCOT hubs represented (South and Houston) were averaged.

Although the LCOE distributions span a broad range, distributions of wholesale electricity prices are well below the total system levelized costs for SMRs. Unless the vision of dramatic cost reduction is realized in the industry, or the cost of electricity is increased by pricing in carbon or other strategic factors, it is unlikely that these reactors will cater to anything but niche applications in the U.S., at least given the estimates generated through this exercise. Scenarios involving the smaller SMR are heavily disadvantaged, and they cater to none of the markets depicted in the graph.

Table 8 lists some existing estimates of SMR overnight capital cost, as reported in the literature. We decided to plug these costs into our cost schedule in order to compare existing estimates and their treatment of uncertainty with our results. Table 9 summarizes the results of this exercise. It reports estimates of LCOE generated by our study to estimates generated by plugging in literature estimates of SMR capital cost.

Table 8. Some existing estimates of SMR overnight cost, adjusted to 2012 dollars.

No.	Year of estimate	Source	Overnight cost ($/kW$_e$)
1	2009	IAEA – 'Generic' SMR (38)	4,200
2	2010	Energy Policy Institute: 'Typical SMR' (101)	5,200
3	2010	Electric Power Research Institute: 'Generic estimate' (102)	5,000 – 5,400
4	2011	Nuclear Energy Agency: '4 × PWR-335' (103)	4,900 – 5,300
5	2011	Nuclear Energy Agency: '5 × PWR-125' (103)	6,800 – 8,300
6	2012	American Security Project: '100MW plant' (104)	2,500
7	2012	Energy Policy Institute: 'Typical SMR' (105)	6,100
8	2012	Anadon et al., expert elicitation, SMR cost in 2030 (113)	1,000 – 16,000

Table 9. Estimates of SMR LCOE generated using overnight cost estimates from the literature, adjusted to 2012 dollars. We assume that the one-unit plants take 3 years to deploy, similar to scenario 4, while the multi-module deployments take 5 years, similar to scenario 3. See table 5 for other assumptions made in these scenarios.

No.	Year of estimate	Source	LCOE ($/MWh) [5th, 50th, 95th]
1	2009	IAEA – 'Generic' SMR (38)	77, 81, 85
2	2010	Energy Policy Institute: 'Typical SMR' (101)	90, 94, 98
3	2010	Electric Power Research Institute: 'Generic estimate' (102)	87, 94, 101
4	2011	Nuclear Energy Agency: '4 × PWR-335' (103)	92, 99, 106
5	2011	Nuclear Energy Agency: '5 × PWR-125' (103)	120, 135, 151
6	2012	American Security Project: '100MW plant' (104)	53, 57, 62
7	2012	Energy Policy Institute: 'Typical SMR' (105)	102, 107, 111

Note that four of the eight estimates of SMR overnight cost in table 8 are point estimates. The reason they generate a range of LCOE values is because the uncertainty in the O&M costs remains built into our cost schedule. That said, literature estimates present a narrower range of potential LCOE values thanks to their treatment of uncertainty, as represented by their narrower range of overnight capital cost estimates, assuming a range is reported at all.

We believe that controlling construction duration, while important from a financial risk management perspective, is not as important a factor as controlling overnight capital cost, given how sensitive the levelized cost is to changes in this parameter. Given the high price of electricity in certain locations, it is possible to construct an economically viable argument for deploying SMRs for some applications, though their deployment may come at a premium compared with other technologies.

4.2 – Comments about the use of levelized cost as a metric of economic viability

LCOE is not without its limitations. Estimates depend heavily on the assumptions that go into any model. When comparing different estimates of the LCOE for the same technology, both careful delineation of the scope of the analysis and subsequent careful accounting can neutralize most criticisms. Assessing LCOEs across technologies, however, is difficult. Below, we briefly summarize some of the limitations of this metric.

When it comes to assessing the LCOE from renewable sources of electricity, it is difficult to fully internalize the cost of these sources' intermittency and variability, though researchers are making progress towards this goal (114, 115). These two factors adversely affect balance of plant components, reducing their lifetimes and consequently increasing maintenance costs.

Moreover, it is arguable that the discounted cash flow model does not account for the value of a diversified energy generation portfolio and devalues a base load power plant's extended lifetime (of up to a potential 80 years in the case of nuclear power). Although levelized cost is an important metric, utilities incorporate other factors and metrics when assessing whether to "green light" a power plant build that are outside the scope of a LCOE calculation.

Because LCOE calculations are generally intended to provide rough estimates of technology costs, such calculations only vaguely account for the strategic costs incurred by site-specific factors, such as the cost of securing a plant's fuel supply for the duration of its lifetime. This is done, for example, by parameterizing "fuel cost", with little regard for political or institutional nuances. It is an acceptable counter-argument, however, that any effort to achieve greater granularity unnecessarily complicates the calculation.

The existing resource mix in a particular location is also somewhat ignored by all but the most detailed LCOE calculations. Calculations made for a specific combined cycle power plant, for instance, may fail to look at the supply side equation on a more strategic, regional or national level, unless the boundaries of the system are extended to consider the need for additional pipelines and such.

The cost of insuring plants against disaster is rarely taken into account in LCOE calculations. Nuclear power LCOE figures rarely account for the cost of potential accidents; in most nations, the largest share of liability for accidents rests with the sovereign entity on whose territory the plant sits. The same argument can be made just as effectively for hydroelectric projects, especially large dams, the construction of which requires the relocation of thousands (sometimes millions) of people: the cost of potential accidents to those downstream of the dam is not included in the LCOE calculation.

Last, but definitely not least, LCOE provides a metric of the private costs of generating electricity. The social costs and benefits might be very different from the LCOE. For example, waste fees for nuclear power are restricted to those required by statute, which might vary considerably from the "true" cost of dealing with the nuclear waste question.

Chapter 5: Insights from a workshop on small modular reactors

This dissertation has thus far focused on integral light water SMRs. These designs are (in some cases, quite substantial) evolutionary improvements on an existing reactor technology with which the world has more than 10,000 reactor-years of experience (116). Vendors have more experience designing LWRs, which is why SMRs of this type are at a more advanced stage of development than non-light water designs: owners are more used to purchasing and operating light water designs, and regulators have more experience overseeing them. Their legacy makes them the most promising candidates for near to mid-term deployment. However, many of the innovations that make SMRs attractive and are required to dramatically increase NPP deployment are restricted to more advanced non-light water designs.

For example, some non-light water concepts (as well as a few advanced light water ones) promise improved operational safety compared to existing technologies. This is defined as either a much lower core damage frequency than regulations call for, which can be achieved by, for instance, defense-in-depth strategies that add multiple robust barriers between the radionuclide inventory in a reactor's core and the environment. Novel fuels, fuel cladding, or core geometry that enhance these barriers would improve operational safety, for example. So would new materials used for either an RPV or containment that are more robust than existing ones. Eliminating the need for operator action, for AC or DC power, or for additional water would also constitute and improvement in operational safety. In fact, designing a reactor that needs none of these three things is colloquially referred to as achieving the "Triple Crown" in nuclear plant safety (41). Some incorporate features that vendors claim make them more resistant to proliferation than light water designs: the use of inert matrix fuel (117), the elimination of on-site refueling (118), and the elimination of waste stockpiling being three examples of such features

(118). Others promise to at least partially tackle the waste question by producing less of it, by making it less attractive to proliferators, or even by utilizing existing waste stockpiles as fuel (119).

On the 18th and 19th of November, 2013, a group of us at Carnegie Mellon University, along with colleagues at the Paul Scherrer Institute (PSI) and the International Risk Governance Council (IRGC), both based in Switzerland, organized a workshop on SMRs. The workshop was hosted on the PSI campus in Baden, Switzerland. The goal of the workshop was to develop a better understanding of the range of views among the community of SMR experts on the nature of the barriers hampering the development and deployment of different SMR designs. Specifically, our objectives were twofold: first, we wanted to determine the technical barriers that stand in the way of different small reactor technologies, and how they might be overcome; second, we wanted to explore institutional arrangements that, if achieved, might allow for the safe and secure mass deployment of SMRs internationally. Here, we present results from the exercises we put to them: a distilled version of this chapter is being prepared for submission to *Energy Policy.*

5.1 – Development of workshop materials

Our goal was to host an event that challenged participants to engage and debate one another, and to answer pointed questions that would fulfill the two objectives presented above. The workshop was consequently light on presentations and heavy on discussion, and on individual and group-based exercises. Recognizing that this is a sensitive subject, and that representatives of several competing firms would be present in the same room and privy to all discussions, we decided to hold the workshop under the Chatham House rule: the content of the discussions and the assessments provided could not be attributed to participants without their explicit permission. Moreover, they were explicitly and repeatedly asked to draw upon their expertise and judgment when answering the questions as individual experts.

Determining the type and magnitude of the technical barriers that hamper the development and deployment of SMRs presented us with a problem. Ultimately, because different SMR designs embrace different technologies and deployment options, and because each of these is claimed to have advantages that make it particularly suitable to fulfill the vision of safe and secure mass deployment, we had to choose a subset of SMRs that was varied enough for an interesting comparative technical assessment to be made. We wanted to determine whether we could identify a subset of SMR-specific design features that stood out in the discussion – for better or for worse – and determine how close each design was to the most optimistic visions of successful SMR deployment.

The process of selecting the set of SMRs to investigate was straightforward. There were several constraints: first, we did not want to overwhelm participants by having them compare too great a number of designs; second, we determined that we needed to contrast land-based reactors with sea-based reactors, so at least one of the latter was necessary; third, we needed at least one – and not more than two – light water SMRs to contrast these with non-light water technologies; and fourth, we needed to incorporate as many different technologies as possible, with ideally each reactor being unique in at least one respect.

After discussions among the organizers, and after consultation with reactor developers, we settled on six SMR designs, all of which are among those listed in table 1 in chapter 2. Here we give a brief overview of these.

Two of the six designs we chose were light water designs. One is U.S.-based Babcock and Wilcox's (B&W) 180MW$_e$ Generation mPower (figure 17), an integral light water SMR that received the first of the DOE's two cooperative funding agreements to guide it through the licensing process (120). The Generation mPower is scheduled for deployment in the early 2020s at the Tennessee Valley Authority's Clinch River site (120), and the submission of its design certification application to the U.S. NRC is due in the third quarter of 2014 (120). The design calls for the underground deployment of a 360MW$_e$ twin-pack, the reactor has a 4-year core refueling interval, and B&W claims that the EPZ can be reduced to within the plant perimeter (41, 43).

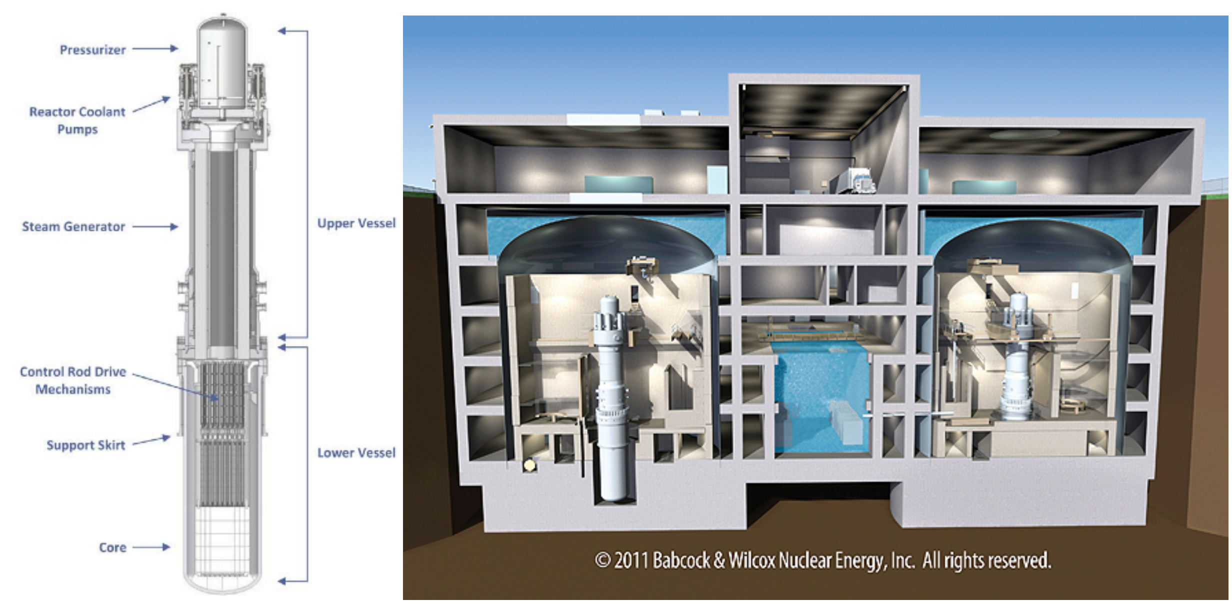


Figure 17. Renderings of the Babcock and Wilcox Generation mPower iPWR module (left, 121), and of the proposed twin-unit plant (right, 122). Used with permission.

The other LWR is the Russia-based OKBM Afrikantov's KLT-40S. A twin-pack of this 35MW$_e$ reactor has been installed in the non-self-propelled vessel *Akademik Lomonosov* to create an FNPP that is being prepared for deployment in northern Russia in 2016 (figure 18). The two vendors' *modi operandi* are quite different. While the mPower reactor would be built by B&W and its associated plant by engineering services firms in the conventional way, the KLT-

40S FNPP would be shipped to customers wishing to "lease" the plant and anchored off their nation's coast. The unit would be owned and operated by organs of Rosatom, an umbrella organization of Russian state-owned firms (123–125). Although both reactors utilize low-enriched uranium (LEU) (i.e. less than 20% ^{235}U), the motivation for choosing them is precisely that they represent very different operational paradigms.

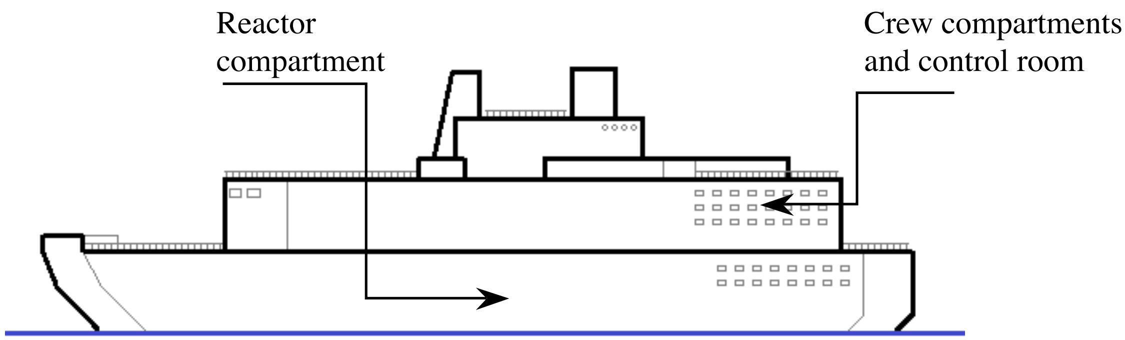


Figure 18. Illustration of the floating nuclear power plant *Akademik Lomonosov*, which will house two OKBM Afrikantov KLT-40S light water SMRs.

The first of the four non-light water designs is Japan-based Toshiba's 4S (figure 19), a $10MW_e$ liquid metal reactor that employs molten sodium as its coolant (a $50MW_e$ option is also available, though we chose to investigate the smaller reactor). Noteworthy features of this reactor include the long refueling interval: the reactor is shipped to the site as a whole and, once fuel is loaded into it, the module is sealed and the unit operates for 30 years. Toshiba will not even install fuel-handling equipment on-site; these are brought in at the end of the 30-year period, and Toshiba will assign one piece of this equipment to multiple units. It utilizes fuel enriched to 19% ^{235}U. Toshiba claims that the design operates without substantial involvement from its operators (126, 127).

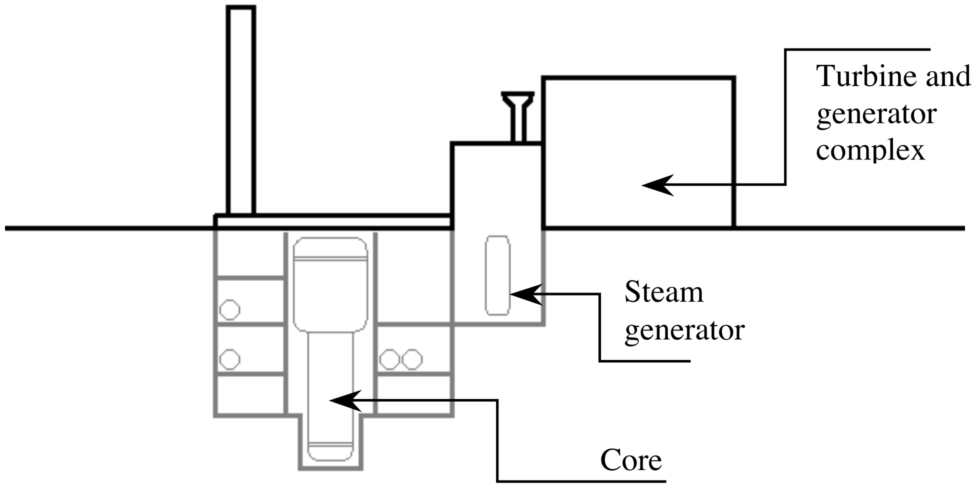


Figure 19. Illustration of the Toshiba 4S liquid metal reactor.

The second non-light water design we investigate is China-based HSNPC Ltd.'s HTR-PM (figure 20), a Tsinghua University-designed 105MW$_e$ pebble-bed, helium-cooled reactor that runs at high temperature and therefore a greater thermal efficiency of 40%. It is designed to be deployed as a 210MW$_e$ twin-pack, and is currently under construction in Rongcheng (33). It utilizes fuel enriched to 8.5% ^{235}U, and, being a pebble-bed reactor, refuels continuously. Its designers claim that, although it is designed for base load operation, it can also function as a load-following unit (128).

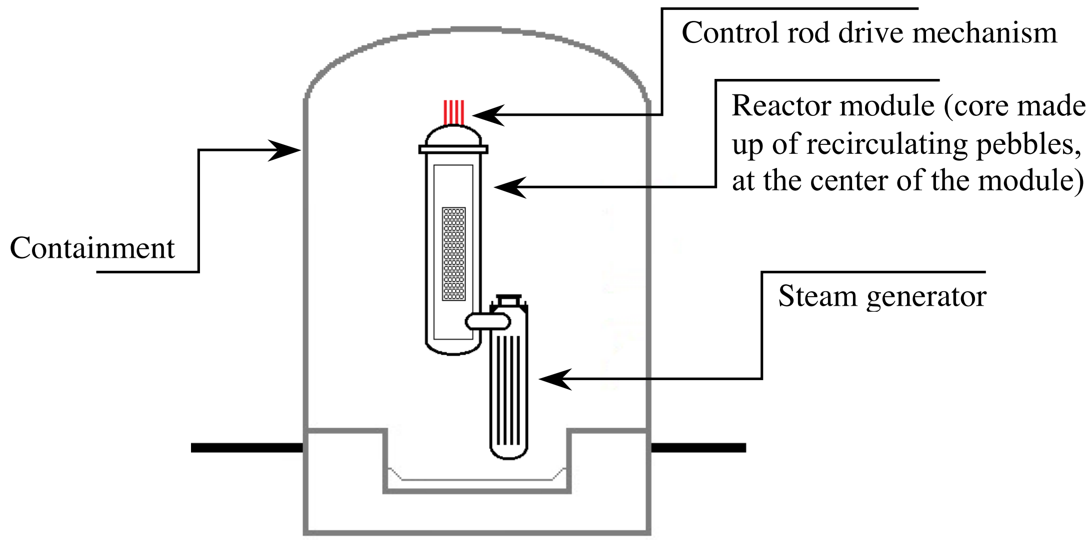


Figure 20. Illustration of the HTR-PM high temperature reactor.

Third in this category, and fifth out of six designs, is the lead bismuth eutectic-cooled SVBR-100 that is being developed in Russia by JSC AKME (figure 21). This is a 100MW$_e$ fast neutron reactor that is designed to eliminate some systems in order to reduce plant complexity and cost, as well as human error. It utilizes fuel enriched to 16% ^{235}U, and is designed with a refueling interval of 7 to 8 years in mind. More than one reactor – up to 16, in fact – can feed their power to the same turbine, creating a multi-module plant (129).

The sixth and last design is U.S.-based General Atomic's Energy Multiplier Module (EM^2), a 265MW$_e$ fast neutron reactor that utilizes the full helium cycle (figure 22). To construct this plant, three modules constituting the NSSS are shipped to the site and interned in a sealed underground concrete vault. The RPV is shipped to the site from the factory with fuel inside. It uses a combined cycle that pushes its efficiency up to 53% and (119), like the SVBR-100 (and, to a lesser extent, the other advanced designs), it can recycle the waste products of LWRs to extract more energy from the uranium fuel. This requires no reprocessing – only re-fabrication of the LWR spent fuel (119). The reactor is designed to operate without refueling for 30 years (130). Characteristics of the six reactors are summarized in table 10 below.

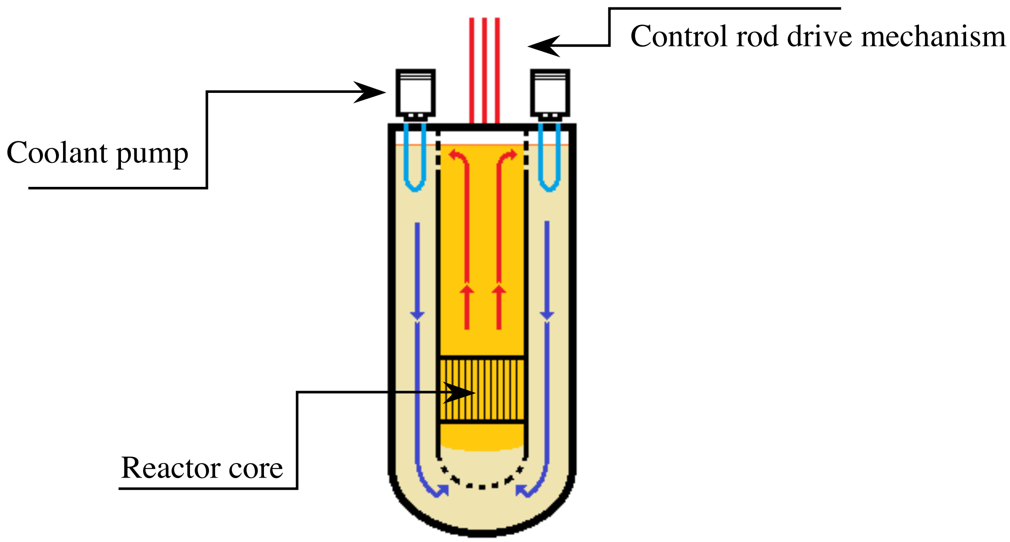


Figure 21. Illustration of the JSC AKME SVBR-100 liquid metal reactor.

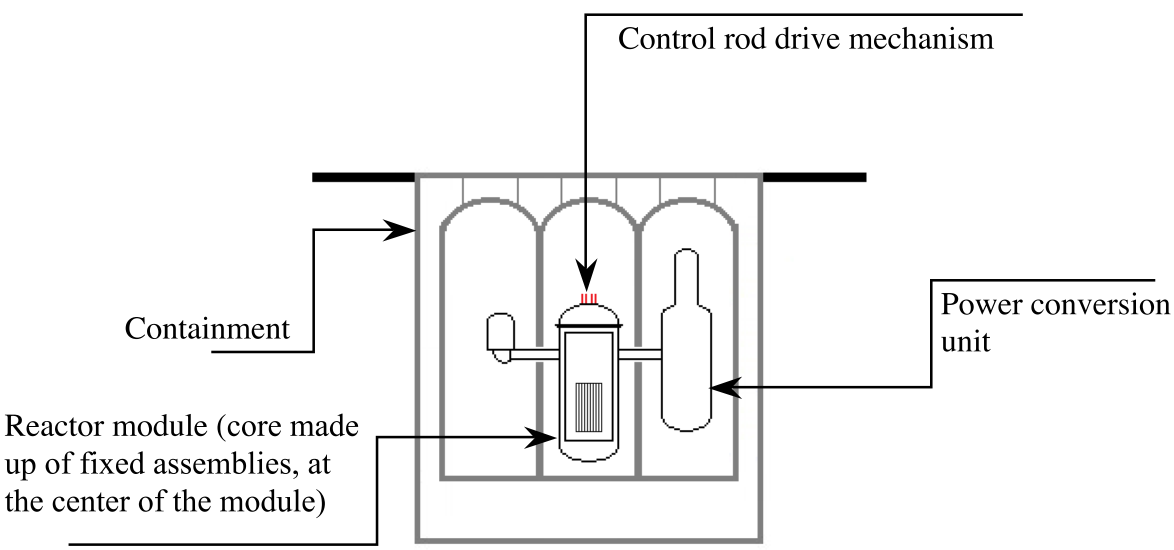


Figure 22. Illustration of the General Atomics Energy Multiplier Module high temperature reactor.

Table 10. A comparison, across various attributes, of the six reactors chosen for investigation at the workshop.

	B&W mPower	KLT 40S	Toshiba 4S	HTR-PM	SVBR 100	GA EM^2
Power output *(MW_e)*	180	2 × 35	10	2 × 105	101	265
RPV height *(m)*	25.3	3.9	24	25.4	7.9	10.6
Underground?	Y	Sea	Y	N	N	Y
Coolant	H_2O	H_2O	Na	He	Pb-Bi eutectic	He
Breeder?	N	N	N	N	N	N
Fuel reprocessed?	N	Y	Optional	N	Optional	Optional
Refueling period *(yrs)*	4	3	30	Cont.	7–8	32
Fuel enrichment (%)	<5	<20	<20	8.5	<20	12 / 6
On-site refueling?	Y	Y	Once	Y	Y	N
Spent fuel on-site	Y	On-board	Y	Y	N	Y

We developed several exercises to assess the six SMR designs; two investigated the differences in user requirements between developed and developing countries; two explored the institutional changes that are necessary for the successful mass deployment of SMRs internationally; one was dedicated to proposing and assessing visions of a world that incorporated SMRs into its energy system; one was reserved for presentations that provided up-to-date information on the state of SMR research and development at the IAEA, at the U.S. NRC, and in various countries; and the last was an open-ended discussion during which participants raised issues they felt the previous seven session had not addressed. Workshop materials are reproduced in appendix B.

Table 11 below lists the participants. We had 40 participants from 11 countries, including China, France, Germany, Japan, Kenya, Korea, Russia, Switzerland, the United Arab Emirates, the United Kingdom, and the United States. The participants included representatives from the IAEA, the U.S. DOE, and GRS in Germany. We acknowledged the need to invite technical representatives from developers of each of the chosen SMR designs. In the end, representatives of five of the six chosen SMR designs joined us in Switzerland. In total, we had 13 senior representatives (chief reactor designs, program managers, or executives) from 9 vendors with active SMR programs. These representatives came from 6 countries active in this field: China, France, Japan, Korea, Russia, and the United States. Participants helped provide definitive answers to our outstanding questions; they were explicitly notified that an audio recording of the discussion was going to be made, and they signed a document confirming that they understood this fact.

Table 11. A list of workshop participants and their affiliations.

	Name	Organization
1	Jamal Al Ahbabi	Emirates Nuclear Energy Corporation
2	Jay Apt	Carnegie Mellon University
3	Kazuo Arie	Toshiba Corporation
4	Kazuhito Asano	Toshiba Corporation
5	Ines Azevedo	Carnegie Mellon University
6	Kennette Benedict	Bulletin of the Atomic Scientists
7	Rita Bowser	Westinghouse Electric Co.
8	Chao Fang	Institute of Nuclear and New Energy Technology, Tsinghua University
9	Steve Fetter	University of Maryland
10	Ashley Finan	Clean Air Task Force
11	Keith Florig	University of Florida
12	Marie-Valentine Florin	International Risk Governance Council
13	Zhihu Gao	China National Nuclear Corporation
14	Jean-Claude Gauthier	AREVA NP
15	Alex Glaser	Princeton University
16	Danielle Goodman	Planergie Group
17	Philipp Hänggi	Alpiq AG, Geschäftsstelle swissnuclear
18	Alexey Kondaurov	JSK AKME-engineering
19	Wolfgang Kröger	ETH Zurich Risk Center
20	Chabane Mazri	International Risk Governance Council
21	Edward McGinnis	U.S. Department of Energy, Office of Intl. Nuclear Energy Policy
22	John Molyneux	Rolls Royce plc
23	Granger Morgan	Carnegie Mellon University
24	Chris Mowry	B&W mPower
25	James Noel	B&W mPower
26	Matt O'Connor	Electric Power Research Institute
27	David Otwoma	Kenya Ministry of Energy and Petroleum
28	John Parmentola	General Atomics
29	Andreas Pautz	Paul Scherrer Institut
30	Shikha Prasad	Carnegie Mellon University

31	Michael Rosenthal	Brookhaven National Laboratory
32	Roger Seban	Électricité de France
33	Danrong Song	Nuclear Power Institute of China
34	Morello Sperandio	AREVA NP
35	Hadid Subki	International Atomic Energy Agency
36	Georgy Toshinsky	JSK AKME-engineering
37	Kiril Velkov	GRS
38	Haitao Wang	Institute of Nuclear and New Energy Technology, Tsinghua University
39	Tony Williams	Axpo
40	Kyun Zee	Korea Atomic Energy Research Institute

5.2 – Technical barriers to small modular reactor development and deployment

As mentioned in the previous section, one of the workshop's eight sessions was dedicated to comparing the six designs in table 10 across a range of criteria relating to reactor security and reactor safety. Having reviewed the many SMR designs put forward by developers worldwide, we judged that some reactors might prove more appropriate for mass global deployment than others. One example of a feature that might make the deployment of SMRs more palatable in emerging nuclear energy states is the elimination of on-site refueling. Reactors with long refueling intervals, or those that do not need to be refueled for their entire lifetime, might make the process of securing the reactor easier. In the case of reactors with long refueling intervals, the rate of increase in the inventory of special nuclear material (SNM) stored outside of the reactor vessel would be lower, and the movement of SNM would be more limited; in the case of reactors that require no refueling for their entire core lifetime, inspectors need not worry about any SNM inventory save for what is in the core. Contrast these two options with the case of a light water SMR that would need to have its fuel replaced once every 24 to 48 months, with the spent fuel stored on-site in pools that would need to remain under safeguards for the entire life of the plant – and perhaps until decommissioning, whenever that happens.

Given the often stark implications posed by the different fuel handing and safety arrangements proposed by developers of different SMRs, the goal of this session was to determine which reactor, if any, has a comparative advantage when it comes to operational safety and non-proliferation. More generally, the discussion that ensued represented an attempt to determine those criteria that participants felt were desirable in a reactor being designed for mass global deployment.

In one exercise, each participant had to choose the reactor design that poses the greatest challenge with respect to each of four criteria. These were:

1. Fresh fuel composition and enrichment levels: some of the fuel required for more exotic reactors has only been fabricated in enough quantities to conduct rudimentary tests, if at all. For example, the infrastructure required to fabricate pebbles for the Chinese HTR-PM demonstration plant was only built once the reactor was approved for construction (131). It is conventional wisdom in both the nuclear industry and in nuclear security circles that the higher a fuel's enrichment levels, the more worrying its use and widespread adoption (132, 133). Even the enrichment capability required to fabricate nuclear fuel at 4.95% ^{235}U enrichment, which is necessary for standard LWRs, is controlled very tightly. Reactors that require uranium enriched beyond the traditional 4.95% required for LWRs are thus immediately viewed with suspicion in both industry and security circles (134). This despite the fact that using uranium at enrichment levels higher than 5% has its advantages – not only do you get more power from a compact reactor, but the refueling interval can be extended to prevent outages *and* reduce the spent fuel inventory to be managed (135–137).
2. Spent fuel composition, handling, and storage: Another important criterion is the amount and type of spent fuel a reactor produces, as well as the arrangements for storing it. Some reactors can operate for decades without refueling (e.g. 119, 126): no SNM will be

stockpiled on-site, as it will all remain in the reactor; no fuel-handling equipment will need to be installed on-site. Other designs will need the same fuel handling apparatus as currently exists in an LWR plant: the reactor will need periodic refueling, and the waste will be stored in spent fuel pools on-site (e.g. 43). The composition of the spent fuel is just as important, and some designs strive to create spent fuel too poisonous or unattractive (thus "self-protecting") to be handled post-irradiation, at least by less sophisticated states and non-state actors (e.g. 130).

3. Core lifetime and refueling plans: Perhaps the most effective way of safeguarding a reactor's fuel inventory is to remove the need for operators to access the core, which is why some developers aim to eliminate on-site refueling: once the core has been exhausted, it is removed intact after a cool-down period and a new one installed (e.g. 26). Those reactors that do require on-site refueling can reduce the frequency of this event, perhaps even to the extent of eliminating the need for fuel handling equipment to be kept on-site, as in the case of the Toshiba 4S design that we explore here (126).
4. Transport of fresh and spent nuclear fuel: Finally, there is the sensitive issue of transporting fresh fuel to the site, both initially and when refueling is required, as well as the management of the spent nuclear fuel stockpile. Again, both the frequency and the location of the refueling operation is key here, for the same reasons discussed above.

As is clear from the above discussion, the four criteria listed above are to a great degree interrelated. For instance, the decision to eliminate on-site refueling throughout the core's three-decade lifetime inevitably leads to changes in fuel transport arrangements, and alters both the type and the amount of fresh fuel required. The longer period of irradiation alters the composition of the spent fuel that needs to be processed after three decades. These caveats were noted during our discussions. Figure 23 below summarizes the evaluations of the six reactor designs attributed by participants across the four criteria. Readers must note that the question asked for the design that represents the greatest challenge; in other words, the greater the "count" on the Y-axis, the more that design is at a disadvantage in the judgment of participants.

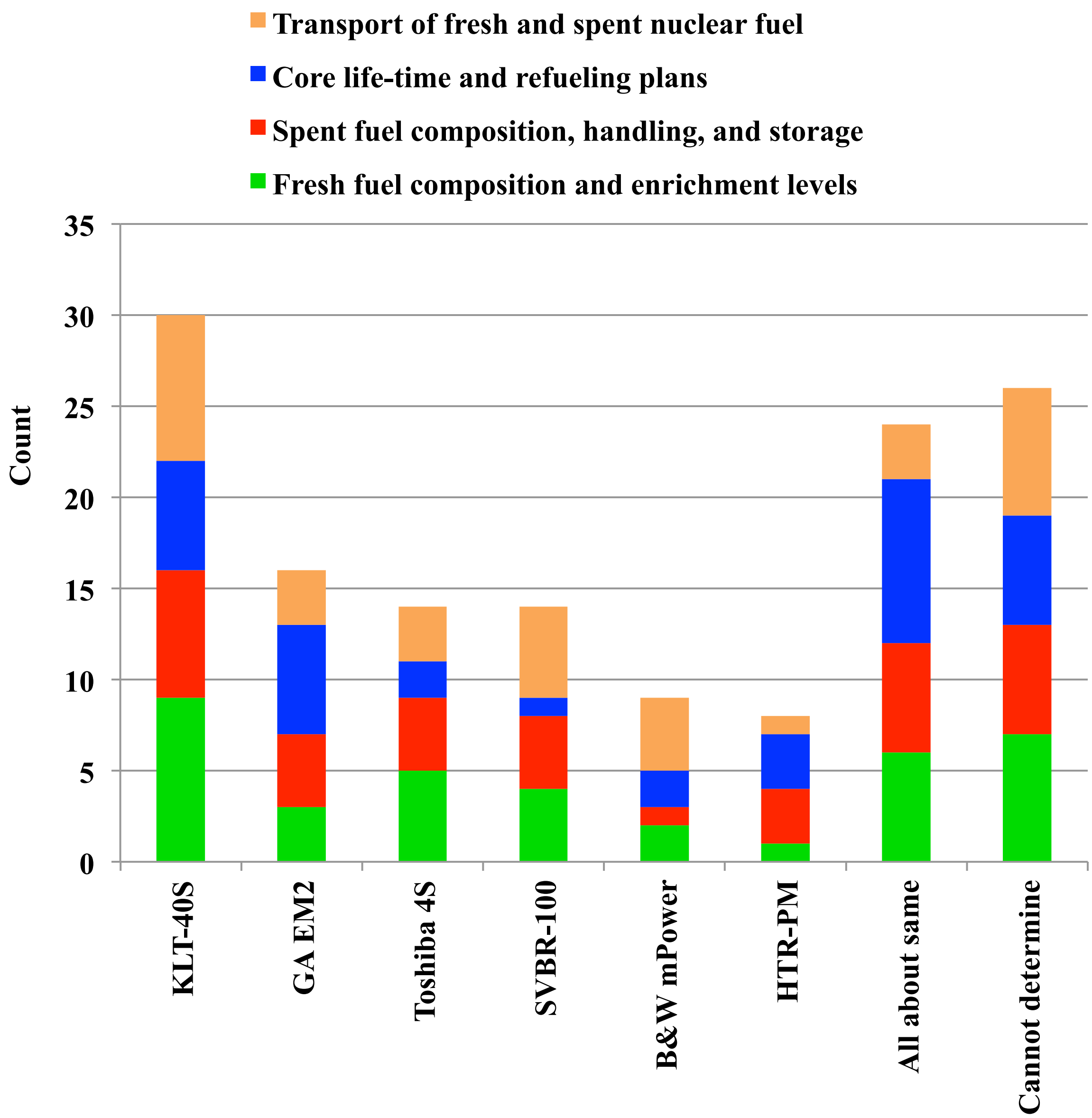


Figure 23. Participants were asked to determine which of the six SMR designs poses the greatest challenge across four security criteria. Given how this question was framed, a higher count implies a potentially riskier reactor design. The discussion revealed that challenging deployment options merit just as much scrutiny as challenging designs.

Several things can be inferred from the counts in figure 23. First is the importance of the "deployment paradigm" and not just the technology. The KLT-40S is the only one of the six designs that has been built and operated previously. Even the mPower, while based on B&W's knowledge of PWR operation, is a novel design. And yet, the KLT-40S is judged to be most challenging in three of the four categories, precisely because its envisioned deployment on a ship raises so many questions. Several participants noted that the arrangement, which requires the plant to be moored off a customer's coast and its customer to accept as little responsibility for its operation as possible, is "nice and clean" in theory, but is bound to raise problems in practice. We must note that representatives from the developer of the KLT-40S were not present at the workshop, which might have led to bias against this design.

Second, fast reactors pose greater challenges than either the HTR or the land-based iPWR. The conventional wisdom that has locked the industry into its existing light water paradigm – that innovative designs, despite their promised advantages, are too complicated and toxic for commercial interests to explore – seems to be valid still. The only developer that was confident exploring a non-LWR design had the backing of a sovereign state: China. This was reflected in the level of confidence other participants placed in the successful commissioning of the HTR project in Rongcheng (33): note that this says nothing about the commercial prospects of this design; we will need to wait years before we can address that question based on actualized cost data as opposed to hearsay and projections.

Higher enrichment levels were considered troubling. Participants acknowledged that fueling reactors with higher enrichment uranium improves their capacity factor and lengthens the refueling interval. Fuels like those used in the EM^2 are considered "less challenging," from a security standpoint, than standard uranium dioxide fuel (with which the world is extremely familiar) enriched to research reactor levels of close to 20% ^{235}U.

We then asked each participant to determine whether one of the six designs posed a greater challenge in terms of licensing than the others. Responses are presented in figure 24 below:

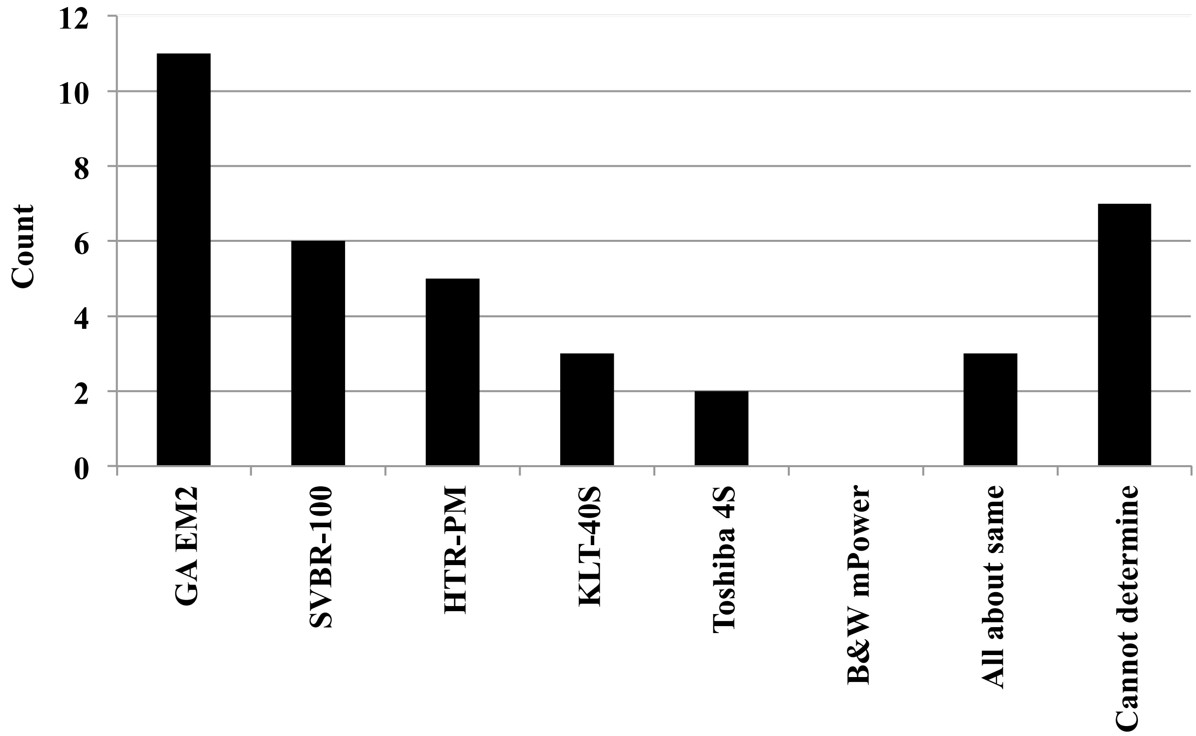


Figure 24. A comparative assessment of the six SMR designs in terms of the licensing challenge they pose. Participants were asked to consider whether one reactor posed a greater challenge in terms of licensing than the others. The greater the departure from the existing LWR regulatory framework, the riskier the licensing process was deemed to be.

The B&W mPower is judged to be the least challenging in terms of licensing, which is hardly a surprise, given that basic ideas and approaches that underlie existing nuclear regulation cater better to the mPower than they do to any other reactor. There are many outstanding issues, of course, but compared to the alternatives, no expert thought it to be the design that challenges the regulations most. Again, the deployment paradigm hinders the ship-based KLT-40S, while the lead-cooled SVBR-100 and helium-cooled EM^2 are, unsurprisingly, considered challenging. The technology of the former powered the now-decommissioned Alfa-class Soviet attack submarines (138), which means that material science and operational challenges have already been encountered, and many overcome (137), though, with the collapse of the Soviet Union, it is unclear how much institutional knowledge has been retained. The EM^2 is considered the most challenging by eleven participants. From the full-helium cycle it employs, to the material science challenges posed by its fuel, to its intricate core geometry, the EM^2 faces many hurdles on its road to becoming a complete design.

Ten participants believed either that the designs all posed similar challenges, or could not determine which design posed the greatest challenge in terms of licensing. Some noted on their workbooks that not enough information exists about some of the non-light water designs to make an informed choice.

5.3 – Institutional challenges facing small modular reactors

Three of the workshop's sessions were dedicated to discussion and exercises that explored the state of current national and international nuclear governance institutions, and elicited opinions about the main challenges they face and suggestions on how to reform or enhance them. In this section, we summarize the main results of each of these sessions.

Challenges to deployment in existing and emerging nuclear energy states: In the lead up to the workshop, we asked participants to provide a list of three characteristics that, in their judgment, help promote the adoption of SMRs. Using their responses, we developed and iteratively refined a list of 15 such characteristics. These are listed in table 12 below. We printed each one of these on a card and asked our participants to select and rank the five that – in their judgment – most help promote the adoption of SMRs, first in OECD countries and then in developing countries.

Table 12. A list of 15 characteristics that promote the adoption of SMRs.

No.	Characteristic
1	On-time, on-budget delivery of the first few plants
2	A build-own-operate paradigm
3	Sealing reactor modules with fuel in the factory and eliminating on-site refueling

4	Decreasing reactor size/inventory to reduce consequences of radioactive release
5	Tagging of nuclear material or international material accounting system
6	Internationalizing the fuel cycle: mining, milling, processing, fabrication, reprocessing, and waste storage
7	Increasing global competition by bringing multiple SMR designs to market
8	An international design certification regime
9	An international regulatory framework
10	Inherent safety of design and improved operational safety
11	Automation of plant operation and fuel handling, allowing for fewer plant operators and personnel
12	Development of global crisis response and crisis management capabilities
13	SMRs that cost less per kWe than conventional reactors
14	Scalability that allows for the ability to serve smaller markets and multi-module deployment
15	Establishing restrictions on the types of fuel used and binding limits on the levels of enrichment

The distinction between OECD and developing countries was used to accommodate differences in the regulatory and crisis response institutions necessary to construct and operate nuclear power plants safely and securely. Obviously, there are non-OECD countries that have constructed and operated NPPs as safely and securely as almost any OECD country, with India, China, and South Africa being three. Conversely, there are OECD countries that have never built an NPP and that, even if they have the institutions necessary to regulate them, do not have experience in this area. These facts were noted during the workshop and, ultimately, we emphasized that we are in fact comparing existing nuclear energy states with newcomer states. In our discussion of the results of this exercise, we will continue to use the original wording of the question as it was put to participants.

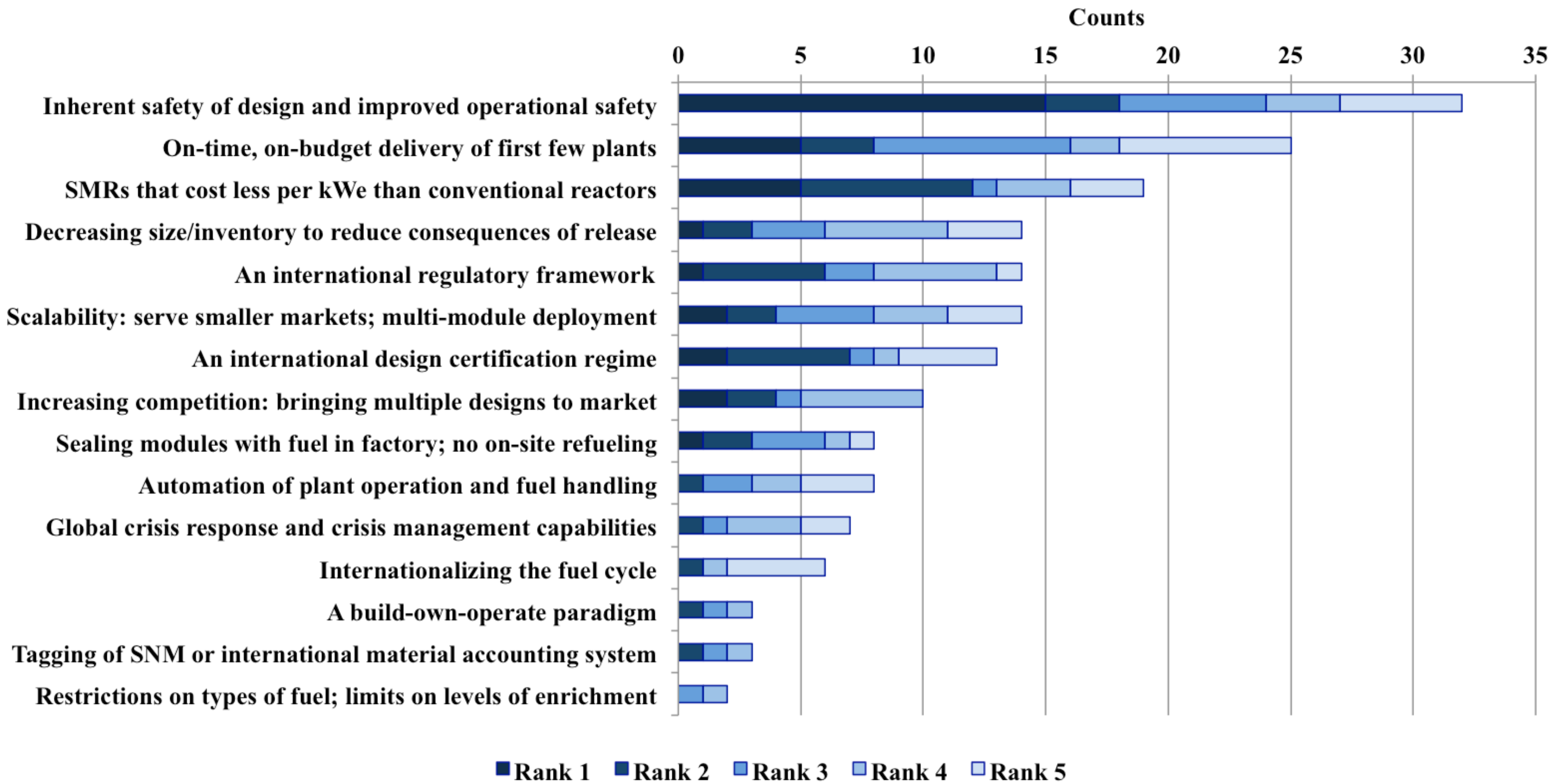


Figure 25. Participants were asked to choose and rank the 5 factors that most contribute to promoting SMR adoption in OECD countries. Safety and economic factors dominate.

Figure 25 shows that, when it comes to OECD countries, safety and economic issues dominate. The three characteristics that matter most in the judgment of our participants are: first, inherent safety of designs and improved operational safety; second, the on-time, on-budget delivery of the first few plants; and third, that SMRs cost less per kW_e than conventional designs.

We were careful to avoid asking questions about potential customers, target markets, or cost data, for multiple reasons. First, issues of confidentiality prevent vendors from answering questions on cost. Second, the presence of representatives from nine competing SMR developers guaranteed that they be tight-lipped on this issue in the presence of their competitors. Third, any estimates of cost provided would have been based on projections: four of the six reactors are incomplete designs, and there are no actualized cost data yet for any of them. We did ask participants to estimate the probability that an SMR design will be available in 20 years with an overnight manufacturing cost (in \$/kWe) that is the same as, or lower than, that of current large Gen III+ reactors. Having answered that question, they were then asked to estimate the probability that an SMR design will be available in 20 years with an overnight manufacturing cost (in \$/kWe) that is at least <u>20% lower</u> than the current cost of large Gen III+ reactors. Results are in figure 26: 70% of respondents to this question believe that, in twenty years, the probability of an SMR costing about the same as what a Gen III+ reactor would currently cost is better than even (>0.5). When asked for the probability of an SMR – again in twenty years – costing 20% less than what a Gen III+ reactor would currently cost, 75% of respondents judged it to be less than even (<0.5).

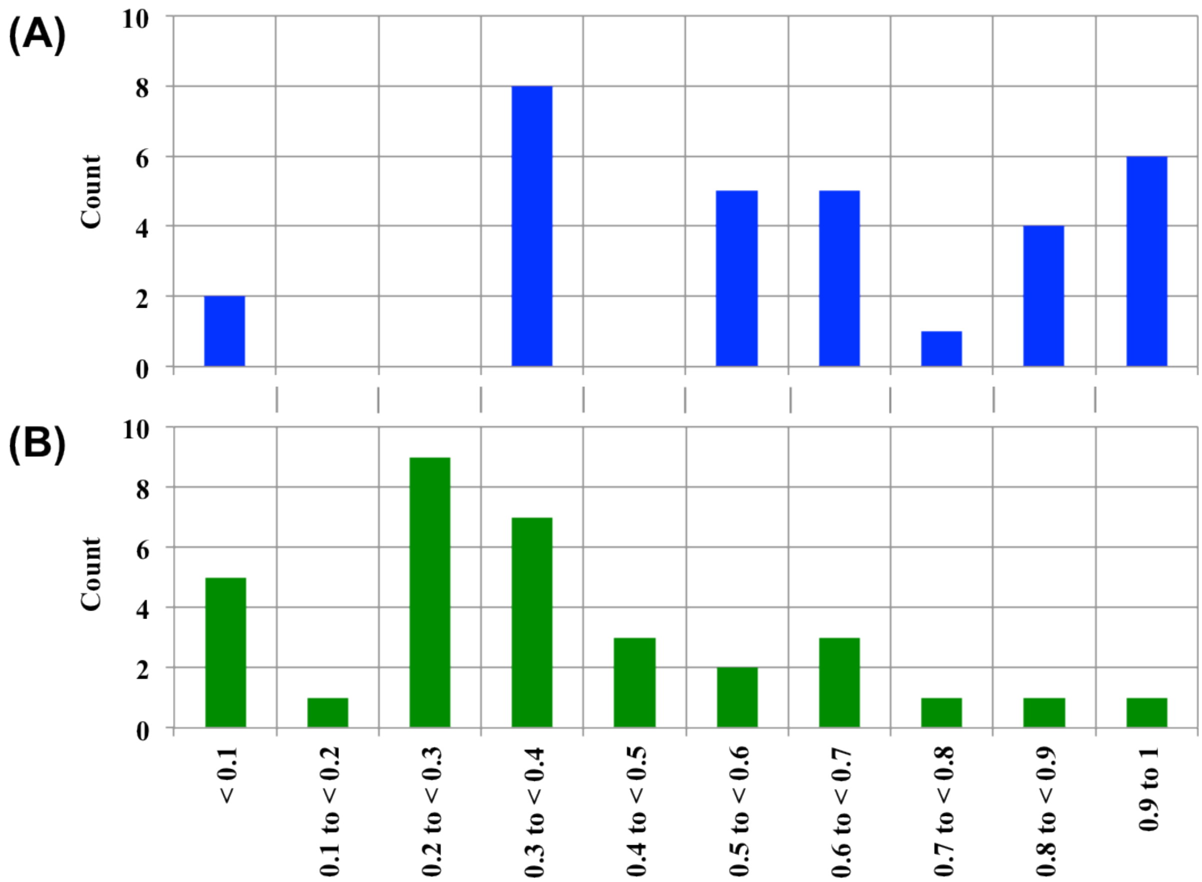


Figure 26. Participants' judgments about the probability that SMR overnight manufacturing costs in 20 years will A) be the same as, or lower than, that of current large Gen III+ reactors, and B) be at least 20% lower than the current cost of large Gen III+ reactors. 31 participants responded to (A); 33 participants responded to (B).

When it comes to developing countries (figure 27), safety figured as prominently as it did with OECD countries. However, the other factors that were deemed of high import were institutional rather than economic: the adoption of international certification and regulatory regimes, as well as the adoption of a build-own-operate (B-O-O) paradigm. In other words, participants felt there should be institutional support – on a trans-national or even international level – for newcomer states that do not have a framework in place to buy, build, and run NPPs on their own. Some of these nations might need help on issues related to security, developing human capital, responding to crises, and/or managing highly technical projects.

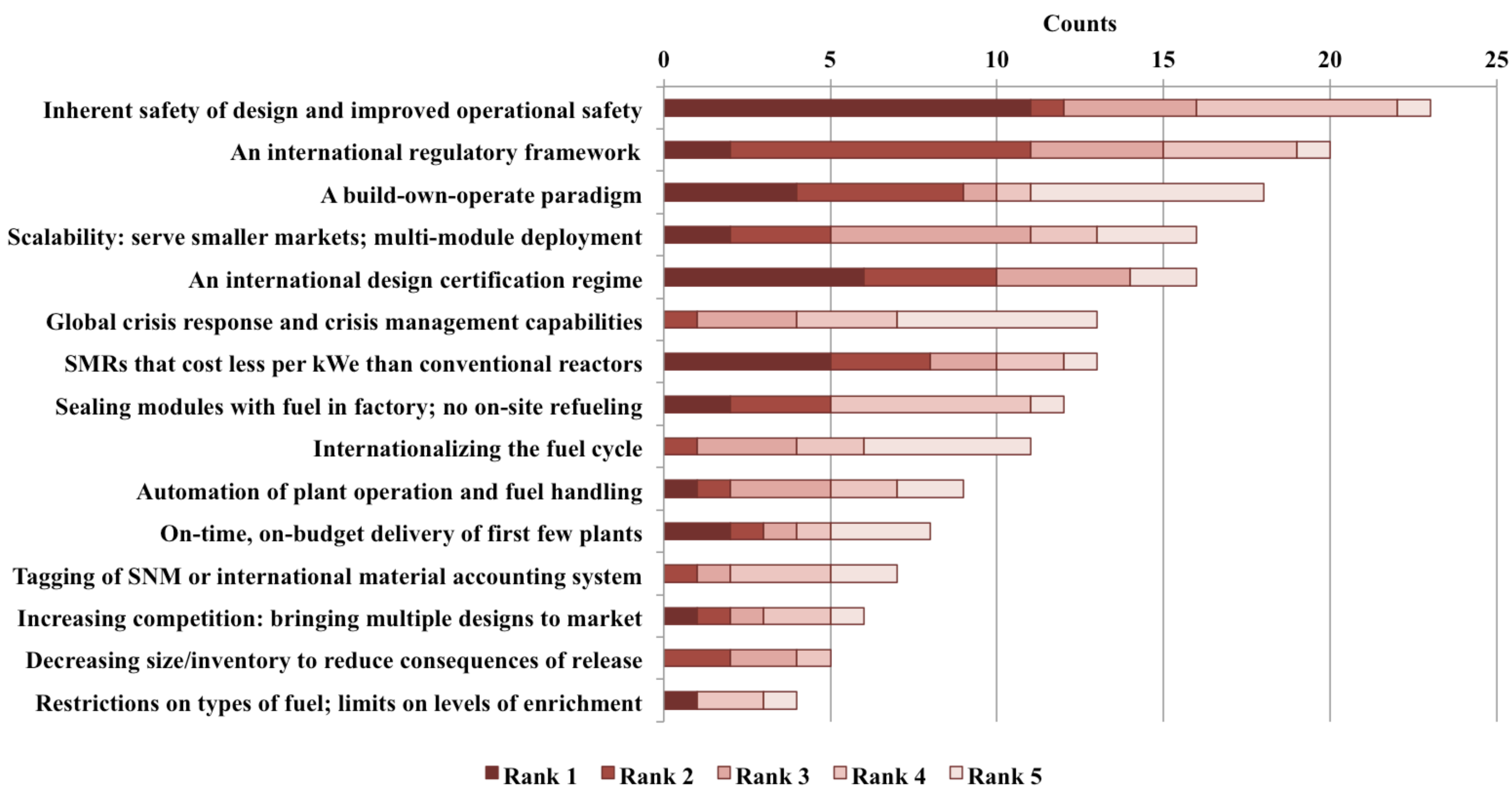


Figure 27. Participants were asked to choose and rank the 5 factors that most contribute to promoting SMR adoption in developing countries. While safety again figures prominently, resolving institutional questions is necessary for SMRs to succeed in the developing world.

The third of these factors was discussed in depth during several sessions. We asked participants how likely it was that such a B-O-O paradigm would exist in 20 years. This novel arrangement would require a nuclear technology vendor to not only build an SMR plant, but also to own and operate the plant for its entire lifetime. The vendor would be responsible for all fuel handling, and also for the removal of spent fuel from the site.

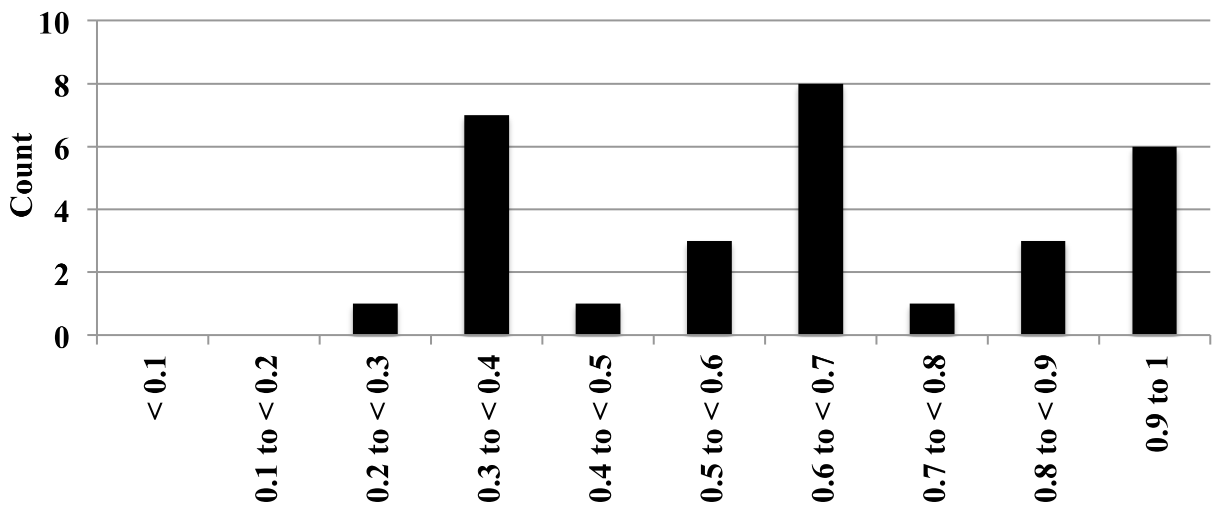


Figure 28. Participants were asked to predict the probability that a reactor manufacturer would offer a build-own-operate package in 20 years' time. Thirty participants responded to this question.

Figure 28 above shows a 70/30 split around the 0.5 mark, with 21 respondents suggesting that it is more likely than not that such a commercial arrangement of this type would exist in 20 years.

We gave each participant two blank cards in addition to the 15 printed ones, in case they wished to emphasize SMR-specific characteristics that did not make it onto our list. Table 13 lists the factors that participants deemed important enough to write in. A few of these are very similar to some of the characteristics in our list (table 12).

Table 13. Additional characteristics that promote the adoption of SMRs. Workshop participants deemed these important enough to "write-in" on the blank cards provided. These are listed in no particular order.

No.	Characteristic
1	LCOE that competes with fossil fuels, such as natural gas, let alone advanced LWRs
2	A suitable range of financing mechanisms, both private and government (multilateral)
3	International training and certification of plant operators and regulators
4	Less up-front costs with competitive overall costs
5	Uneventful operating experience of first few plants and continued quiet with fleet of existing large NPPs
6	High modularization in factory manufacturing
7	SMRs that cost less per kW_e than local electricity production costs at the time of SMR operation.
8	Credible, fair, transparent, international public engagement mechanisms

Building a list of institutional challenges to SMR deployment: We presented participants with a list of four institutional barriers that, in our view, have to be addressed in order to achieve the safe and secure mass deployment of SMRs. At the outset, and despite objections that generated vigorous discussion and debate, we asked participants to assume: first, that mass factory production of SMRs has become a reality; second, that costs have come down to the point that they are at or below those of other base-load sources of electricity and process heat; and third, that a technically adequate arrangement has been devised to deal with waste in a secure way. When pressed as to what the third assumption entailed, we presented a vision of a world where waste would be processed for final storage either in an internationally supervised repository, or in repositories hosted by one or more nations that the world deems to be responsible.

After a protracted discussion that saw workshop participants refine the scope of the four challenges and expand the list, they were asked to rank the barriers in terms of difficulty. Note that a letter was assigned to each to facilitate the ranking exercise. After the 60-minute discussion, the list grew from the original 4 barriers to 10. A discussion of each of these is in order, where practices that fall under each category are presented. Note that these constitute examples and not an exhaustive list of such practices.

Concerns about proliferation of nuclear materials (P): This category encompassed all threats to conduct acts of sabotage against nuclear facilities, regardless of where that threat originates or what part of the fuel cycle is targeted. These include not only the threat from terrorists who seek to compromise nuclear facilities, or who seek to weaponize SNM acquired from any part of the fuel cycle, but also the threat from nuclear non-proliferation treaty (NPT) signatories who cheat on their obligations, or non-NPT signatories who seek illicit nuclear materials. In fact, we even considered the fruits of poor material control and accounting (MC&A) practices to be part of this category.

Political and regulatory restrictions on trans-boundary flows in nuclear technology (T): Many such barriers to NPP deployment already exist, including elaborate export control practices and restrictions in the transfer of nuclear-related human capital. A two-tiered system of nuclear trade exists today that divides nations based on their level of economic development and even their past and/or current political leanings. The perpetuation of such a system would make it difficult for SMRs to achieve mass global deployment.

In practice, this system manifests itself not only in international agreements and groupings, but also in national export control restrictions. The existing barriers were put in place gradually: whenever the issue of nuclear proliferation rose to prominence as a result of geopolitical developments, additional rules were implemented and security tightened. If restrictions continue to increase due to future geopolitical developments, it might be difficult to deploy SMRs on a truly global scale. And, if SMRs are deployed in a “responsible” country today – setting aside the question of what constitutes a responsible country – there can be no guarantee that this country will remain responsible in future. The result might be a backlash against (or at least a stain on the record of) exporting nations; French involvement in the Israeli nuclear project (139–141) and Canadian involvement in the Indian one (142–144) are two examples to consider.

Public concerns about reactor safety and/or waste (S): Nuclear power has always been viewed as problematic in the court of public opinion (47, 48). Evidence is emerging that, even in nations with limited civic participation in public affairs, populations are starting to speak out against this technology (145). It is difficult to imagine that existing public perception issues surrounding nuclear power will not manifest themselves with SMRs. And, if there are safety-related "events" at an SMR plant (or even at large plants), that might bolster opposition to the technology. Even if we assume the waste question has been answered, short of eliminating the waste, concerns about the security and environmental impacts at waste sites will always be raised.

Finally, the most the nuclear industry and national strategists have been able to achieve in the way of public acceptance of nuclear power is the framing of the technology as a Faustian bargain, which is not new in this field (146). Attempts to engender a "reluctant acceptance" of nuclear power, which will be discussed in greater detail in the next chapter, are volatile and unwise, and risk aggravating the many other political and financial challenges facing the technology.

Inadequate institutional infrastructures (I): This issue generated the most debate. Although participants acknowledged its import, it was clear that few had though about it systematically. No participant was willing or able to sketch a reasonably complete specific roadmap for how to improve any of the institutions relevant to nuclear governance, although a number of interesting ideas were floated. Inadequate institutional support would challenge SMRs if, for example, there was little collaboration among national regulators during design certification. This would lead to different deployment rules for the same SMR unit depending on its location. Similarly, the presence of inexperienced national regulators in newcomer states, or incompetent ones in any state, would seriously challenge efforts to deploy SMRs in large numbers. Insufficient emergency response capacity, a subject of great debate during our workshop, is another example of inadequate institutional capacity. Finally, whether the IAEA and the World Association of Nuclear Operators (WANO) need to play a larger role when it comes to SMR deployment are controversial questions, though the status quo would also hamper efforts to deploy SMRs in meaningfully large numbers.

Lack of a greenhouse gas control regime (A): This barrier to SMR adoption, proposed by a workshop participant, was intensely debated. There was a consensus that, without a regulatory regime that placed an explicit or implicit price on emissions of carbon dioxide, the assumptions upon which our exercise was based would not materialize anyway. This is because we assumed in the exercise that the cost of SMRs relative to other technologies is low enough for vendors to justify their mass production. SMRs, even if they were affordable, would not be economically competitive (the distinction between these two concepts was emphasized) in a world that is not committed to seriously curbing greenhouse gas emissions.

Lack of mature, diverse supply chain (B): This is clearly a serious challenge in *today's* world. However, our scenario assumed that SMR mass production had become a reality, and we argued that this implied that the nuclear supply chain had grown enough to handle the new paradigm. Therefore, during the discussion, we objected to the inclusion of this factor as a barrier, but a sufficient number of participants supported its addition.

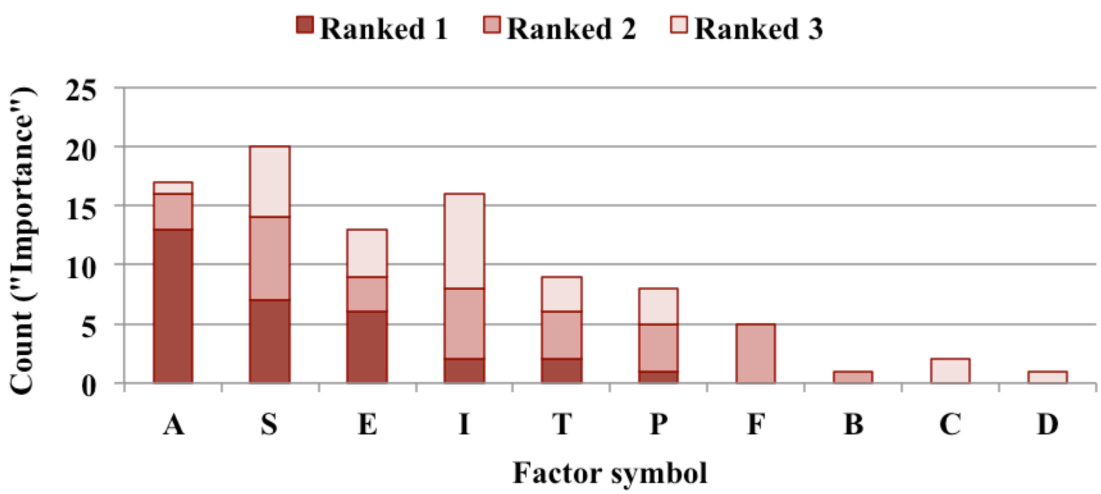
Absence of a very different waste environment (low volume, no proliferation value) (C): This barrier, proposed by a workshop participant, does merit explicit inclusion. Although we assumed in the exercise that the waste issue had been "addressed", the questions of waste composition and volume were left open. The participant who suggested this barrier noted that not all solutions are equal, and those that are talked about most will *not* neutralize this concern. In this participant's judgment, the ultimate goal of the industry should be to render waste unusable by proliferators, first through a significant reduction in its volume (through reprocessing), then by ensuring that the isotopes that remain in spent fuel are of no proliferation value.

Lack of progress on nuclear arms control and disarmament (D): The movement towards arms control and disarmament began with the Partial Test Ban Treaty (PTBT) in 1963. The record since has been rather mixed. Although the world has made substantial progress in reducing the total number of nuclear warheads (the events of the Cold War, and its eventual end, did help this process along), the number of nuclear states has increased from the five that existed when the NPT came into force in 1970 to 9 today. Even the recent record is blemished. For instance, while the New Strategic Arms Reduction Treaty (New START) between the U.S. and Russia, which entered force in 2011, is rightly hailed as a success (147), 2002 saw the withdrawal of the U.S. from the Anti-Ballistic Missile (ABM) Treaty (148). More importantly, the India exception weakened the global nuclear nonproliferation regime (149). Positive developments over the past twenty years include Ukraine's abandonment of nuclear weapons at the end of the Cold War (150); South Africa too stands as an example of a state that completely dismantled its nuclear weapons program and stockpile (151).

Efforts to eliminate nuclear weapons started soon after their inception (50), but progress towards their elimination has been uneven, whether among the nuclear-armed superpowers during the Cold War (152) or among countries in different regions that pledged never to acquire them (153). The fact that they serve little military utility is now widely recognized in academic, political, and even military circles (154–156). The suspension of movement towards this goal, or any weakening of the international community's commitment to non-proliferation, might deal a devastating blow to the rejection of the development, use, and stockpiling of weapons of mass destruction (WMD) that has become an international norm. North Korea, Libya, Syria, Chechen separatists, and the AQ Khan proliferation ring have already tested this commitment when it comes to SNM, and Libya and Syria have tested it with respect to other WMDs. Again, the international community's response to these violations of global norms have been far from uniformly impressive, but to discuss this fact further is to digress greatly from the topic of this dissertation. Suffice to say: the weakening of global norms could embolden state and non-state actors to exploit SMRs.

Political instability; political lack of support; financial instability (E): Another factor that participants included is political and financial instability, regardless of location, but especially in small newcomer states that might be struggling with more issues than just energy. Three examples highlight the range of scenarios discussed: first, countries that attempt to finance construction through loans from international organizations, only to see their economic conditions worsen and have default become a possibility; second, governments that commit to SMRs, only to be deposed by agents that then seek either to divert SNM to nefarious ends, or to use the integrity of the NPP as a bargaining chip in negotiations; third, nations that, faced with an accident at another plant, decide to abandon their ambitions in dramatic fashion to secure short-term political gain. Fukushima has generated examples of the third scenario (157, 158).

The nuclear premium (nuclear liability, insurance, and financing) (F): Before private firms were prepared to embark on building nuclear plants in the U.S., it was necessary to create a legal system that placed a cap on their liability in the event of an accident. The controversial Price-Anderson Act provided such a cap, currently set at more than $12 billion (159). Globally, there are several conventions governing liability in the case of an accident. Given the lack of a global regime, there exist substantial gaps in the current international framework: more than half of the world's nuclear fleet is not covered by any regime currently in effect. If the world does not try and change this, it might hamper efforts to deploy SMRs in certain parts of the world.



A	No GHG control regime
S	Public concerns
E	Political and financial stability
I	Inadequate institutional infrastructures
T	Restrictions on trans-boundary flows in nuclear technology
P	Concerns about proliferation
F	The nuclear premium (liability, insurance, financing)
B	Lack of a mature supply chain
C	Absence of a diff. waste environment
D	No progress on arms control and disarmament

Figure 29. Workshop participants were asked to rank 10 institutional barriers that might hamper the safe, secure, and global deployment of SMRs.

Figure 29 shows the results of this exercise: four barriers stand out. The lack of a greenhouse gas control regime (**A**) was considered a major barrier because, without such a regime, the potential economic non-viability of SMRs would render them an irrelevance anyway. Political and financial instability (**E**), public concerns about nuclear safety and waste (**S**), and inadequate national and international institutions (**I**) were also judged to be of great importance.

5.4 – Three views of a future world of small modular reactors

To address the institutional challenges highlighted in section 5.3 above would require major changes to the international nuclear governance regime. We wanted participants to consider alternative universes in which SMRs might be deployed, and one way to do that was to present them with different futures and ask them for their judgment as to how likely and how desirable these future are. Ultimately, our goal was to expand the set of alternative deployment arrangements they were considering, and perhaps generate discussion about how to achieve the alternatives they considered desirable, or to achieve – at the very least – changes in specific institutions or components of the international nuclear governance regime that would lead to a world in which SMRs could be deployed safely and securely. After much discussion and several iterations, we settled on three visions, each of which will be discussed below.

One radical vision of a future world of SMRs, suggested by our colleagues at the University of Maryland, requires a new international agreement to be negotiated among supplier states, a primary stipulation of which is the formation of a globally representative consortium of manufacturers and fuel suppliers. This consortium's role would be to:

1. Harmonize policy and practices for legacy contracts, stipulating that large LWRs can be sold only in countries that comply with the nuclear governance regime;

2. Manage the manufacture at protected locations of sealed, pre-fueled SMR reactors for all export markets under a full B-O-O regime and require that all spent sealed SMR reactor modules be returned at the end of their service life to an internationally approved and supervised originating facility; and
3. Establish and operate a global liability regime and an international accounting system for all fissionable isotopes.

We labeled this scenario the **strict export limitations** scenario, and discussed it at length with our participants. Between this heavily restricted world and the **business as usual (BAU)** scenario, discussed below, participants helped us develop a **mixed export limitations** scenario.

In a **BAU** scenario, all existing elements of the international nuclear governance regime remain in place:

1. Exports of nuclear technologies are limited to countries that are in compliance with their obligations under the NPT and have instituted full-scope IAEA safeguards, or, if outside the NPT, are in compliance with nonproliferation and nuclear security and safety guidelines suggested by the Nuclear Suppliers Group (NSG);
2. No new international agreements with legally binding obligations are made about the export, use, or operation of nuclear technologies;
3. Management and operation of SMRs remain responsibility of operators in host nations, including spent fuel management; and
4. Aside from legal obligations stemming from the NPT and other existing nuclear conventions, and commitments stemming from NSG guidelines, manufacturers of SMRs located in different nations face different levels of nationally imposed controls on export of nuclear technology and know-how.

In a **mixed export limitations** scenario, there is a new multi-national agreement among supplier states that:

1. Places no restrictions on SMR export to nations that comply with the international nuclear governance regime outlined in **the BAU future**, under the assumption that international entities such as IAEA have full resources to exercise their full responsibilities; and
2. Allows export of SMR systems of any design to any nation so long as the exporting entity, nation, or region retains full management and operating responsibility across the entire fuel cycle and retrieves and returns all spent fuel to its country of origin, or to an internationally supervised facility.

After a discussion of the three futures, participants performed two chip allocation exercises, each of which saw them divide 20 chips among the three futures described above. First, participants were asked which of the three futures was most likely. Second, participants were asked which of the three futures was most desirable for the safe and secure mass deployment of SMRs. The results are summarized in table 14 below.

Table 14. Three visions of a future world of SMRs. In the judgment of participants, the most likely future would see the status quo (BAU) more or less maintained. 34 participants participated in this exercise.

	Most likely future (% of chips allocated)	**Most desirable future (% of chips allocated)**
Business-as-usual	75	45
Mixed export limitation	18	33
Strict export limitations	7	22

Not one expert believed the **strict export limitations** scenario to be most likely; 90% of participants chose **BAU** as the most likely scenario. As table 14 shows, of the total number of chips, three quarters were allocated to the **BAU** scenario; less than a fifth were allocated to the **mixed export limitations** future; and only 7% to the **strict export limitations** future.

There was a lack of consensus about the most desirable future. Only a fifth of the chips were allocated to the **strict export limitations** future advanced by our colleagues at Maryland: it was judged the least attractive one. The **mixed export limitations** future received 33% of all chips, and the **BAU** scenario received 45% of all chips.

It is perhaps unsurprising that this group of participants would consider **BAU** a desirable paradigm. Industry was heavily represented, and it is generally reticent about accepting any changes to the status quo, especially when these come in the form of tighter regulation or evolutions in international norms. A subset of participants argued that they could not see how the mass deployment of SMRs would challenge the existing system, and why new visions need to be promulgated. One participant said that, “somehow, you infer with your questioning that [the business as usual paradigm] is not satisfactory. And this is something I cannot really agree with.” Another noted, "I think when it comes to safeguards and proliferation, we have the regulations in place. We have the treaties… and I also believe that if we deliver sealed units to these countries, just the fact that they're screwed on tight is not going to stop them from getting at the nuclear materials if they really wanted to… And I don't think we should take over responsibility from a state that wants to implement nuclear power.” This participant went on to suggest an alternative scenario, which was “a stepped approach to business as usual. If a vendor wants to sell to a state, then they commit to that and can help support the state to become more competent by training their personnel until they're in a position to operate the plant themselves. In principle, everything we need is in place. We just need to tweak it here and there to cater to countries [that] do not have nuclear power competence themselves… And we need to build it with time. I would support business as usual in a stepped manner." We could not see the difference between this vision and business as usual. Several participants strongly objected to the setup of this exercise, and thought that we were underhandedly advocating a roadmap for the future of nuclear trade, with the **strict export limitations** scenario our ultimate goal. Even when we asked participants to consider the ideal presented in the **strict export limitations** scenario, there was palpable frustration and a genuine inability to envision how this situation would even come about. In other words, none of the people present had thought enough about the longer-term issues involved in the development and international deployment of SMRs to envision how the world might arrive at such a future given where we are today, or indeed whether the world should be working to reach a very different future. To us, that simple fact was the most profound take-away from the workshop.

5.5 – Further insights from the workshop

In this section, we will highlight important points that were raised by workshop participants over the course of the two days.

On the technical front, vendors who lacked support from a sponsor with deep pockets expressed frustration with the state of innovation in the nuclear industry. Ideas that seek to change the cost, operational, and/or waste paradigms are at a serious disadvantage: we still live in an LWR world, and changing elements of the existing formula forces existing national and international institutions out of their comfort zone. This fact, and the expense required to develop a new design, constitute large barriers to entry.

As discussed above, on the institutional front, it is clear that much needs to change, but among the 40 participants at our workshop, there were few ideas and no consensus on how to move forward:

First, the benefits of innovative ownership schemes that seek to change nuclear power's operational paradigm, such as the B-O-O model that we were quite excited about going into this workshop, are very much open for debate. In light of concerns about proliferation, we had expected participants to adopt a positive view of the possibility that developing countries might "lease" power from a low-carbon energy source without owning and operating it, and without managing its waste. However, some participants argued that such an option was not desirable, because developing countries have additional motivations for acquiring civilian nuclear power plants, including developing human capital, accruing national prestige, cementing institutionalization, and engendering a sense of responsibility. One participant asked, "to what extent is training for folks in-country likely to be a major factor in the relative attractiveness of alternative designs?" Answering his own question, he continued, "from a proliferation perspective, the B-O-O may be a superior option because it limits the spread of technical knowledge. But I could imagine that from the perspective of a host nation, for example, that you would like engineers to become proficient in nuclear engineering as a consequence of having built an SMR."

There are strategic reasons for not adopting the B-O-O model also. One participant, simulating the thought process of a newcomer state, first acknowledged the merits of the B-O-O model before adding, "I will not step from oil dependence to Russian electricity dependence [this in reference to the KLT-40S FNPP]."

Second, and following up on the previous point, some participants argued that every country that wants a nuclear plant will have to develop some measure of capability to manage that plant or the consequences of potential mishaps. Withholding such capabilities in the name of "non-proliferation" is not only patronizing to these countries, it can be quite dangerous for them and for their neighbors, not to mention for the future of the industry as a whole. Articulating this argument, one participant noted, "as soon as you commit and make a decision to import nuclear power, I think you need to develop your own capability. Nuclear power is a long-term project and it comes with long-term commitments, like decommissioning and waste management and so on. As assurance, to the public and to yourself, you want to develop your own capability, so you know how to handle nuclear power in addition to providing jobs and all that... Of course you trust the vendor to do everything right, but you want the assurance that, if something happens, you can at least handle it." As we expected, national sovereignty emerged as a challenge to efforts to reform the existing regime. Said one participant, "the sovereignty issue, I think, is huge. Each country, ultimately, needs to own their plans to deploy nuclear energy. And it's really important that they own it so they answer to the citizens of that country. Because, first of all, it's not a question of **if** you have a safety issue that gets public attention in the country and the market. It's a question of **when**… I think that, if you're not careful, one can take it too far and, if you have a build-own-operate where a foreign government or company owns the plant, if there's a safety issue, being able to respond as government representatives to your citizens, as opposed to [having foreign powers dominate your response]… Ultimately, no matter what, if you want to deploy nuclear power in your country, you've got to have ownership of the most basic aspects of safety and security in that country, and not have the appearance that you're relying on a foreign entity." One participant dissented from the view that knowledge transfer should be restricted, but approached the argument from a different angle, "it seems to me that we need as many people as possible to have the expertise to be able to develop [nuclear technology], to figure out other ways of dealing with spent fuel, and a whole host of problems that nobody has really solved yet… It seems a shame that we cut off some people because they somehow politically don't fit with our image of what a nuclear expert should look like... If there's a reduction in human capital and knowledge in the [developed world], then… it needs to come from somewhere, and why not have it come from those countries which are accepting or building nuclear reactors? You don't want to horde the knowledge, because then you enter a neocolonial relationship, where some can have the knowledge and some can't, [which is] a fairly insidious… way to run a global nuclear industry."

Third, participants made it clear that most customers will seek some measure of localization if they choose to embark on an industrial project as complex as an NPP. Relying entirely on foreign suppliers might be considered strategically unwise. That said, "I think we should be clear by what we mean by knowledge transfer. If I'm seeking knowledge transfer from [a vendor], I might not be talking about building [the product] from nuts and bolts, but I might want to be able to manufacture a valve for [it]. So I think we need to have a bit of nuance." Another participant noted, "the thing that we sometimes forget is that these are 60 to 80 year investments within a country, and so of course people will want to have some capability to at least maintain and have some sense of operation... surely there will be several transitions in the course of that timeframe and that provides that opportunity for that local indigenous capability. There is the construction itself, and in any construction, there's a practical aspect, in that part of the supply chain has to be local – even in modular construction, there simply has to be a local element… And the challenge is finding that right balance between standardization and the right quality of components, and then that local expertise."

Fourth, in the view of many participants, developing a centralized international or multinational system to regulate SMR deployment verges on the impossible if we want to address the climate problem in the next decade or two. And if we are trying to craft a new international nuclear governance regime for the post-2050 time period, it is perhaps unwise to predict or set the trajectory of efforts towards this regime today. One possible model is the two-pronged approach of strengthening the IAEA's oversight of the global NPP fleet and developing WANO into a far stronger agency with the same level of collaboration between operators as seen in INPO in the U.S. "One strong candidate, moving forward, is a reformed WANO." In fact, a degree of consensus was achieved around this point, suggested by a participant who explained, "to the extent that we're talking about experienced nuclear technology countries sending their technology to small developing countries, handling the certification is the easier part, because that's being handled by countries that are selling the reactors, and we have several very good regulators for that. The operation… is where we need to focus more on safety, because there isn't the infrastructure there and another country can't just come in and provide that… INPO in the U.S. is a very good model… INPO has a stick, which is that their ratings of reactors influence insurance ratings for the owners and operators of reactors. WANO doesn't have that, and there should be some sort of stick that WANO could have similar to INPO. That's one idea for improving operational safety." As in every facet of our discussion of the international nuclear governance regime, concerns about the erosion of national sovereignty present a formidable hurdle to progress on this front, and collaborative efforts to reform WANO would be an attempt to improve safety without implementing sweeping international reforms.

Fifth, according to some participants, crafting a new international system might not even be desirable. Several suggested that the status quo is decent, and dissented from our suggestions that it might not be. As mentioned earlier, one noted, "somehow, you infer with your questioning that [the business as usual paradigm] is not satisfactory. And this is something I cannot really agree with." But given the scale of the challenge and the number of issues that must be addressed by any effort to reform the system, it was also clear few are thinking more than a few years into the future. The focus of most was on developing their reactors or finding new customers.

Sixth, "the major elements of the nuclear governance regime have been working better than you give them credit for," was one participant's retort to our call for ideas on how the system needs to be enhanced. "I'm not sure what you mean [when you assert that the international nuclear governance system is] weak… That regime is fairly extensive, [but] I certainly wouldn't suggest that there couldn't be improvements… I would say that, for SMR deployment, there's not much more needed than what's already there. Because most of these SMRs don't really increase the amount of proliferation risk, so what's there is enough." Those laws and guidelines that are necessary already exist, and no overhaul of the system is necessary. Once SMRs are deployed widely and globally, the world will obviously need to dedicate more resources to the maintenance of a robust nuclear governance regime, but that is all that is necessary: the safeguards that currently exist need only be extended to cover all SMR plants.

Seventh, if we still find it necessary to brainstorm ideas for changing or enhancing the nuclear governance regime, it is unwise to proceed as if nations will act irresponsibly *unless* they are placed under the control of an international governance regime, or as if vendors would amorally sell these reactors without carefully considering the risk of each sale. As one participant noted, "that's factored into a vendor's view of liability. I would imagine there's quite a bit of liability if your reactor is basically controlled by an unstable regime… It's more about vendor risk-aversion in terms of where they'd pursue opportunities.” Another executive from a competing vendor concurred, noting, “I will choose my customers very carefully, or I will end up with zero customers pretty quickly.”

Eighth, several experts reiterated the sheer scale of the job necessary to de-carbonize the power system. Hundreds of large plants need to be built to mitigate greenhouse gas emissions from dirty base load generators (39), and this fact puts into perspective the diseconomies of scale faced by SMRs. As one pessimistic participant noted in his workbook, “if you are not building large nuclear power plants, you will need thousands of SMRs to satisfy the small ‘nuclear wedge’ part of the solution. I do not think I need to add anything to this statement.”

Ninth, and finally, towards the end of the workshop one participant interjected that, “[while] we have been here for two days now, I still don’t know what the point of SMRs is.” What problem, the participant asked, were SMRs trying to solve? Anyone can generate a list of their potential advantages, but the participant suggested that each of these advantages arguably has a “flip side.” The case for SMR deployment is hardly indisputable, in other words. A participant went on to publish a piece in the *Bulletin of the Atomic Scientists* emphasizing this exchange (160).

Chapter 6: Synthesizing the results of our efforts

Workshop participants tried to propose solutions to the problems facing SMR deployment. Here, we highlight some of their more interesting suggestions, synthesizing what we have learned in our investigation of this topic, before closing with the conclusions of our work.

6.1 – Institutional challenges that can be resolved with additional research

Challenge 1: A realistic identification of potential customers is necessary. It might be foolhardy at this stage for reactor developers and researchers to pinpoint those applications for which "SMRs might provide the answer," unless they are willing to embark on detailed case studies that engage all relevant stakeholders in the community hosting the SMR. Some customers for whom SMRs are well suited – in *our* judgment – might not even consider them as they move forward. It is imperative to recognize the difference between affordability and economic competitiveness: SMRs, even if they were affordable, might prove economically uncompetitive in certain applications.

We would like to stress this point by discussing what is, in our judgment, a more straightforward example than most. As oil production platforms have evolved in the past two decades to extract oil from deeper waters and in more hostile environments, their energy demands have increased. Taking the North Sea at the turn of the century as our case study, we note that most production platforms in Norwegian waters relied on gas turbine generators housed within the platforms (166); gas turbines were scalable enough to be accommodated in platforms, and the security of supply certainly was not an issue. Flaring this valuable gas, producers would not only lose the product, they would pay a penalty in the form of Norway's tax on carbon emissions. Indeed, even the feeding of this gas to a gas turbine was environmentally expensive: at the turn of the century, offshore gas turbines were "the largest source [24%] of CO_2-emissions in Norway and Norwegian waters" (161); there was a desire to supply production platforms with electricity from a source with lower carbon intensity than gas turbine generators.

The amount of power an oil production platform needs depends on many things, including field characteristics, process characteristics (e.g. is enhanced oil recovery, or EOR, being performed?), on-board product processing requirements, method of transportation of products, and the size of the rig and its staff complement. In 2001, the biggest platforms required "more than $100MW_e$," with the total power required for large fields "close to $500MW_e$" (161).

The idea of placing a small SMR on each platform, or even of placing a large SMR on the biggest platform and then transmitting electricity to its neighbors, might seem appealing. However, it is a perfect illustration of a case where an SMR, despite being *affordable*, is not *competitive*. From our elicitation results in chapter 3, we can estimate the overnight cost of a $45MW_e$ SMR to be between \$90 million and \$1.1 billion, while the overnight cost of a $225MW_e$ would range from \$450 million to \$2.7 billion. Table 15 below illustrates the percentage of the cost of four of the world's largest production platforms that a single $45MW_e$ SMR represents.

Table 15. The cost of four oil production platforms in the Gulf of Mexico.

Platform	Cost (\$ x 10^6)	Year of estimate	Cost in 2012 \$ (\$ x 10^6)	Source	% of cost rep. by $45MW_e$ SMR
Perdido *(Shell)*	6,700	2008	7,000	(162)	1% – 16%
Tahiti *(Chevron)*	4,700	2008	5,000	(162)	2% – 22%
Thunder Horse *(BP)*	8,300	2008	8,900	(162)	1% – 12%
Ursa *(Shell)*	1,450	2000	1,900	(163)	5% – 58%

Three points bear emphasis: first, the crude inflation from original dollars to year 2012 dollars was accomplished using the CPI for the purpose of this illustrative exercise. To properly adjust these figures, a combination of indices would most likely have to be used. Second, the cost estimate for the $45MW_e$ SMR refers to overnight cost only. It excludes owners' cost, such as installation, licensing, and the host of measures that would probably have to be taken to secure a reactor in such an unusual setting. Third, assuming you can shield the crew and the environment on a production platform from radiation, a rule of thumb among Norwegian oilmen is that each ton of equipment brought to the platform would require ten times that amount of construction material for a platform that rests on the seabed, and more than that for floating platforms (161). It is not hyperbole to declare that a $45MW_e$ SMR weighing 700 tons before fueling (164), along with its balance of plant components, including its concrete structure, large emergency water inventory, and additional measures to prevent it succumbing to hurricanes or other intense storms, would pose installation challenges. For comparative purposes, consider that *Chevron's* Tahiti, their largest structure in the Gulf of Mexico, weighs 21,000 tons and needs a $30MW_e$ power plant (165).

A careful consideration of alternatives must guide the decision-making process of potential SMR customers, regardless of the cost of the reactors.

Challenge 2: Nuclear safety and security can be enhanced not just through sweeping international treaties, but also through bilateral and multilateral agreements. Prospective customers in emerging nuclear energy states must move towards developing and signing such agreements. Sections 5.3 and 5.5 made the case that efforts at establishing international certification and licensing regimes, while desirable, are unlikely to lead anywhere in the foreseeable future. In the absence of sweeping international arrangements, we believe that bilateral and multilateral arrangements would also work well. A developing country wishing to purchase an American reactor that had already been certified by the U.S. NRC could, for instance, arrange for its national nuclear regulator to collaborate with the U.S. NRC to acquire sufficient information and technical expertise to review the documentation and achieve expedient design certification at home. Certification of a reactor design in a major market would make its certification in others easier, and bilateral agreements, such as the ones the United Arab Emirates (UAE) engaged in with multiple nations at the outset of its civilian nuclear power program, can facilitate collaboration among nations. That said, efforts must simultaneously be redoubled to grant the IAEA sufficient manpower and resources, and perhaps greater authority, to fulfill its mission in a world where nuclear reactors are adopted more widely. Similarly, efforts to standardize codes in the nuclear industry must be accelerated to truly internationalize the industry, engender cooperation among industry, and improve quality, which has the added benefit of reducing costs (166). Efforts towards this end have already started, using the aerospace industry as a model (167).

Challenge 3: A determination must be made of the minimum emergency infrastructure needed for the safe and secure operation of a SMR plant. Notwithstanding quality construction and competent regulation, the myth of absolute safety needs to be abandoned for good. We have established that, irrespective of the level of responsibility a vendor takes for plant construction and operation, the effects of a nuclear accident will manifest themselves most seriously in the area around the plant. Every nation wishing to purchase an SMR must therefore accept the burden of responsibility that comes with the acquisition of an NPP, and that includes developing a level of emergency response and crisis management infrastructure robust enough to cope with the effects of potential accidents. While vendors can design ways to increase coping time in the event of an accident, no vendor can guarantee accident-free operation.[*] Again, the idea that nuclear power's social institutions must remain

[*] One workshop participant stressed this point, while also advancing the notion that not every nation can develop a robust crisis response infrastructure. He noted, "there is no in-place international emergency response capability, and I'm not even sure what that would look like. If you're talking about widely dispersed - in terms of deployment of SMRs around the world, I'd imagine that they'd effectively be widely dispersed - so [in my view] it's more about

active in perpetuity is not new (146). Bilateral and multilateral initiatives help accelerate the development of such infrastructure, as existing nuclear energy states share their expertise, equipment, and technology with emerging nuclear energy states. On the level of plant operators, it is imperative that WANO strive to achieve the level of information-sharing exhibited by INPO in the U.S. Strengthening WANO will not be an easy task, but information-sharing works in the interest of all plant operators, and thus of their customers and of the nuclear industry at large.

Questions about institutional robustness will undoubtedly be raised if mass deployment of SMRs appears likely. Perhaps the most effective rebuttal to those advocating a particular arrangement is to remind them that the three most well known nuclear accidents – Three Mile Island, Chernobyl, and Fukushima – occurred in three countries with considerably different institutions and safety cultures.

Challenge 4 – Efforts to develop a global liability regime, or to ensure that all reactors are covered by the regimes that currently exist, must be accelerated. No global third party nuclear liability regime exists. There are multiple conventions that states subscribe to and, given that some subscribe to none, there exist substantial gaps in the current international framework: more than half of the world's nuclear fleet is not covered by any liability regime currently in effect.

The main conventions at the moment are the Original Paris Convention (1960) and the Original Vienna Convention (1963). The former stipulates a liability amount of 15 million special drawing rights (SDRs, where 1 SDR = $1.54 as of March 27, 2014; 168), while the latter scales with the price of gold per troy ounce. As of March 27, 2014, the Vienna Convention

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what's loosely defined as coping time, and again, if you look at a Fukushima type event, where the reactor was designed with a coping time of hours, you really need to move that into the weeks time-frame... you need to create sufficient time for the global community to respond to a significant issue and, in that way, you bypass a very impractical requirement that each country that starts deploying one SMR has some type of emergency response capability. It really doesn't seem to be economic or practical to go down that path."

stipulates a minimum liability amount of $185 million (169). The Brussels Supplementary Convention of 1963 increased the Paris Convention's liability amounts from 15 million SDRs to 300 million (170).

More recently, efforts have been made to increase the liability amounts in acknowledgment of the devastating effects of nuclear accidents. The Revised Paris Convention of 2004 increases the liability amount to a minimum of 700 million euros, while the revised Vienna Convention of 1997 increases its liability amount to 300 million SDRs. A Convention on Supplementary Compensation (1997) stipulates a minimum of 600 million SDRs. Neither this latter Convention nor the Revised Paris Convention of 2004 are yet in force (170). Efforts to modernize the nuclear liability regime involve steering countries towards ratification of the revised conventions, since they increase minimum liability amounts, cover a wider range of damages, and explicitly declare that "grave natural disasters" are no grounds for exoneration (170). Efforts are ongoing to harmonize nuclear liability law within the EU, which gives a sense of the scale of the effort required to harmonize global nuclear liability regimes. Movement towards this goal will be very slow.

Some existing nuclear energy states have not ratified any of the conventions, including India, China, South Africa, and Canada. Most of the developing world has yet to ratify any. In fact, some developing nations considering a nuclear program probably could not afford the minimum liability amounts they would be responsible for – in the event of an accident, these nations would possibly default. The international community might not be willing to develop some form of shared international liability cap. However, if SMRs show promise and seem destined for mass deployment, national nuclear industries might force such efforts into being as each lobbies its government to share liability for their products with customer nations.

Another idea that is worth exploring is the development of shared regional liability caps. Many nations share grid infrastructure with their neighbors; regions are becoming electrically more interconnected. Since the UAE plans to feed power from its reactors into a Gulf Cooperation Council (GCC) grid, as does France into the European Union (EU) grid, perhaps those nations that benefit from NPPs despite hosting none themselves could contribute to mitigating the consequences of a nuclear accident in their region. Bilateral approaches with powerful neighbors or supplier nations, or shared regional liability caps, might be worth investigating as countries explore the notion of acquiring an SMR.

Challenge 5: Visions of a future world of SMRs need to become either more realistic, by acknowledging existing technical and institutional constraints, or more sophisticated, by proposing a roadmap to overcome these constraints in pursuit of their goals. Our work suggests that the vision of reactors that can be fabricated and fueled in an internationally supervised factory, shipped to a site where they operate without refueling, and then removed upon end-of-life to an internationally supervised waste processing facility presents formidable technical challenges, virtually insurmountable institutional ones, and is perhaps undesirable. For one thing, it might perpetuate the two-tiered system of nuclear trade and investment that we are currently locked in, thus producing resentment among players in the lower tier. Efforts can be made to avoid the creation of such a system by, for example, building multinational consortia and exploiting existing elements of the governance regime to the full instead of pushing for new agreements.

Also of concern is the fact that the technical barriers are great if we wish to achieve this vision in the two or three-decade timeframe we are entertaining. As our discussions during the workshop made clear, each of the three elements the vision puts forth: the shipment of the fabricated reactor loaded with fuel, the long core-lives envisioned, and the post-operation transport and processing in a dedicated facility, presents a technical problem that remains unsolved on a commercial scale. Several participants argued that there is a considerable risk that fuel in most designs would be damaged during shipping.[†] For one thing, shipping fueled light water reactors to a site would be out of the question, given concerns about criticality. Long core-lives require intricate core geometry, large core inventories, high fuel enrichment, advanced forms of controls such as moveable reflectors, or a combination of the above characteristics. Some of these are themselves security concerns, such as high fuel enrichment; those that are not remain unproven in anything but small-scale laboratory settings. Finally, post-operation transport would be possible only after a cool-down period for most designs, since reactors would continue to generate decay heat even after shutdown. We are not suggesting that designing such a reactor is impossible; only that existing designs are not consistent with this vision, and some characteristics required by this vision might pose challenges of their own.

Even if the technical challenges can be overcome through an Apollo-scale investment in SMRs by multiple countries, the institutional barriers to achieving this vision are legion. The nuances of such a treaty would likely dwarf those of the NPT, and that itself was a controversial treaty, mainly because it enshrined the two-tiered system in international law. The biggest problem with this vision is that it overturns 50 years of international norms by severely curtailing access to nuclear materials, technology, equipment, and expertise for exclusively peaceful purposes. Not only does it eliminate the right to pursue any part of the fuel cycle other than

[†] Summarizing conversations among his company's engineers about this issue, one workshop participant noted that, "they have serious reservations about transporting such a core, and the potential for damage to the core, even slight changes to the core that result from transport. And so, there are technical issues here that need to be addressed that aren't addressed when people" develop these visions.

operating a reactor, it curtails freedom of choice by offering a limited subset of designs from which customers would choose.

Challenge 6: The question of public attitudes to nuclear power needs to be revisited with new tools, as do efforts to communicate risk to communities hosting NPPs, as opposed to the survey-based approaches of the past few decades. This challenge was brought up several times during our discussions. Over the past few decades, many studies have surveyed public perception of nuclear power in both developed and developing countries.

To trace just one peculiar evolution of public sentiment towards nuclear power, consider the case of the UK, where there has been much recent academic work on the public perception of nuclear energy. The literature there has focused on people's attitudes to the technology, and it has explored the framing of the nuclear energy debate in the UK mainstream media. Results from this discourse suggest that Britons favor nuclear power least among energy generation technologies. In fact, they associate it exclusively with negative images (171). That said, when the argument for nuclear power is framed as a Faustian bargain, a "reluctant acceptance" of the technology is engendered (172–174). The usual construction of this argument is: nuclear power is bad, but it has its benefits, and besides, we cannot do without it. The literature also suggests that, since Chernobyl, but especially since the turn of this century, there has been a deliberate attempt by several influential organs in the UK, including the mainstream media, the nuclear industry, and the Government, to reframe nuclear power as a Faustian bargain, precisely to engender such reluctant acceptance of the technology (172). In our opinion, it is dangerous to base such large energy investments on a foundation so weak. Unless SMRs can provide a leap in operational safety that changes this situation, unless the public – for one reason or another – finds them to be of less concern than large reactors, despite the nuclear stigma, or unless a more effective method of risk communication engenders genuine public acceptance of the technology, perhaps even by addressing long-standing concerns regarding safety and waste management, some populations might reject them outright.

6.2 – Conclusions

These six chapters summarized the results of several investigations into the viability of small modular nuclear reactors. The sensitivity associated with all projects in the nuclear space, and issues of economic propriety associated with individual designs in such an active area of technology development, contributed to making this task difficult. Adding to this level of difficulty, SMRs come in a wide range of sizes and technologies, which makes analyzing the category as a whole, as opposed to a subset of reactors, practically impossible.

That is why, three years ago, we started looking at that subset of SMRs that we considered to be the most promising candidates for near to mid-term deployment: integral light water SMRs. We conducted a technically detailed elicitation of expert assessments of their capital costs and construction duration, focusing on five hypothetical reactor deployment scenarios, proposed by nuclear technology vendors, that involved a large reactor and two light water SMRs. Consistent with the uncertainty introduced by past cost overruns and construction delays, median estimates of the cost of new large plants varied by more than a factor of 2.5. Expert judgments about likely SMR costs displayed an even wider range. Median estimates for a $45MW_e$ SMR ranged from \$4,000 to \$16,300/kW_e, and from \$3,200 to \$7,100/kW_e for a $225MW_e$ SMR. There was consensus that SMRs could be built and brought on line about two years faster than large reactors. Experts identified more affordable unit cost, factory fabrication, and shorter construction schedules as factors that may make light water SMRs economically viable, though it was fairly obvious that these reactors do not constitute a paradigm shift when it comes to nuclear power's safety and security.

Using the results of the expert elicitation, specifically the estimates of overnight cost and construction duration generated during the study, we calculated levelized cost of electricity values for four of the five scenarios. For the large plant, median levelized cost estimates ranged from \$56 to \$120 per MWh. Median estimates of levelized cost ranged from \$77 to \$240 per MWh for a 45MW_e SMR, and from \$65 to \$120 per MWh for a 225MW_e unit. We concluded that controlling construction duration is important, especially from the standpoint of financial risk management. That said, it was also obvious that our levelized cost estimates were most sensitive to changes in the capital cost estimates. Given the price of electricity in some parts of the U.S., we conclude that it is possible to construct an economic argument for deploying SMRs in some locations, or for certain niche applications.

One conclusion of the above studies is that it is most unlikely that the vision of dramatic cost reduction through factory mass production will be realized by this first generation of integral light water designs. Even the lower bounds of our estimates suggested that this vision could not realistically be achieved by the SMRs that will come to market over the next decade or two.

We thus decided to investigate the technical and institutional barriers hampering the development and deployment of advanced reactor designs by organizing an invitational workshop, which became an integrated assessment of various designs and of the institutional innovations required to bring SMRs to market.

We gathered some valuable insights from the workshop. The institutional factors that are judged to pose the greatest challenge to the mass deployment of SMRs are: the lack of a greenhouse gas control regime; political and financial instability; public concerns about nuclear safety and waste; and inadequate national and international institutions.

When presented with scenarios that radically departed from the status quo, it was clear that participants – most of whom came from industry – had not given such alternative futures much thought. The problem was twofold: first, industry representatives are generally skeptical of radical departures from current practice, especially if new regulatory approaches are key to these policy innovations; second, most simply could not imagine a roadmap to arriving at a vision of the future so different from what currently exists. When asked what factors most help promote SMR adoption in OECD and developing countries, economic factors dominate the list of characteristics that most contribute to their promotion in OECD countries but, when it comes to developing countries, institutional factors are regarded as being of highest import. Safety of design and safety in operation are judged the most important characteristic on both lists.

The decision to build a nuclear power plant depends on a multitude of social, political, institutional, economic, environmental, and infrastructural factors. It should not be taken lightly, whether by an existing nuclear energy state or an emerging one. It seems likely that every country will need to develop some level of technical and institutional support for any nuclear plant it chooses to build.

That said, given the sheer scale of the climate problem, and the growing appreciation of the limitations of integrating variable and intermittent renewables into the energy system, it is important to allow SMR vendors to either establish or disprove the viability of these designs, some of which show great innovation and promise. One would be remiss to dismiss nuclear power out of hand, because it is hard to see how the world can decarbonize its energy system without adopting a portfolio of "everything we've got."

Chapter 7: References

1. Bupp IC, Derian J (1978) *Light water: how the nuclear dream dissolved* (Basic Books, Inc., NY), pp 7–8.

2. International Atomic Energy Agency (2014) Power reactor information system: operational & long-term shutdown reactors. *International Atomic Energy* Agency, Vienna, Austria. Accessed March 24, 2014. Available at: http://www.iaea.org/PRIS/WorldStatistics/OperationalReactorsByType.aspx

3. U.S Nuclear Regulatory Commission (2013) Pressurized water reactors. *U.S. Nuclear Regulatory Commission*. Accessed March 25, 2014. Available at: http://www.nrc.gov/reactors/pwrs.html

4. Lamarsh JR, Baratta AJ. (2001) *Introduction to Nuclear Engineering* (Prentice Hall, Upper Saddle River, NJ), third edition, pp 137–143.

5. U.S Nuclear Regulatory Commission (2013) Boiling water reactors. *U.S. Nuclear Regulatory Commission*. Accessed March 25, 2014. Available at: http://www.nrc.gov/reactors/bwrs.html

6. International Atomic Energy Agency (2013) Nuclear power reactors in the world. *International Atomic Energy* Agency, Vienna, Austria, table 7.

7. International Atomic Energy Agency (2014) Power reactor information system. *International Atomic Energy* Agency, Vienna, Austria. Accessed March 24, 2014. Available at: http://www.iaea.org/PRIS/home.aspx

8. Marques JG (2011) Review of generation-III/III+ fission reactors, in *Nuclear energy encyclopedia: science, technology, and applications*, eds Krivit SB, Lehr JH, Kingery TB (John Wiley & Sons Inc., Hoboken, NJ), pp 231–254.

9. World Nuclear Association (2014) Heavy manufacturing of power plants. *World Nuclear Association*. Accessed March 24, 2014. Available at: http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Heavy-Manufacturing-of-Power-Plants/

10. Kidd S (2009) New nuclear build – sufficient supply capability? *Nuclear Engineering International*. Accessed March 24, 2014. Available at: http://www.neimagazine.com/opinion/opinionnew-nuclear-build-sufficient-supply-capability

11. Takemoto Y, Katz A (2008) Samurai-sword maker's reactor monopoly may cool nuclear revival. *Bloomberg*. Accessed March 24, 2014. Available at: http://www.bloomberg.com/apps/news?pid=newsarchive&sid=aaVMzCTMz3ms

12. U.S. Nuclear Regulatory Commission (2014) Information digest, 2013–2014. *U.S. Nuclear Regulatory Commission* (*NUREG-1350, Volume* 25), appendix A.

13. International Atomic Energy Agency (2013) Nuclear power reactors in the world. Figure 5.

14. Schwitters R, Allen T, Back C, Barletta W, Dahlburg J, Hosemann P, Remer J, Rosner R, Teter D, Was G, Yang R, Zinkle S (2013) Renewing licenses for the nation's nuclear power plants: a report by the APS panel on public affairs. *American Physical Society*.

15. International Energy Agency (2013) Key world energy statistics. *International Energy Agency*.

16. Monitz E (2011) Why we still need nuclear power: making clean energy safe and affordable. *Foreign Affairs* 90(6). Accessed March 24, 2014. Available at: http://www.foreignaffairs.com/articles/136544/ernest-moniz/why-we-still-need-nuclear-power

17. Kharecha PA, Kutscher CF, Hansen JE, Mazria E (2010) Options for near-term phaseout of CO_2 emissions from coal use in the United States. *Environ Sci Technol* 44(11):4050–4062.

18. Kharecha PA, Hansen JE (2013) Response to comment on "prevented mortality and greenhouse gas emissions from historical and projected nuclear power." *Environ Sci Technol* 47(12):6718–6719.

19. Monbiot G (2011) Greens must not prioritize renewables over climate change. *The Guardian*. Accessed March 24, 2014. Available at: http://www.theguardian.com/environment/georgemonbiot/2011/aug/08/greens-renewables-climate-change

20. Monbiot G (2011) Why Fukushima made me stop worrying and love nuclear power. *The Guardian*. Accessed March 24, 2014. Available at: http://www.theguardian.com/commentisfree/2011/mar/21/pro-nuclear-japan-fukushima

21. Revkin AC (2013) To those influencing environmental policy but opposed to nuclear power. *The New York Times*. Accessed March 24, 2014. Available at: http://dotearth.blogs.nytimes.com/2013/11/03/to-those-influencing-environmental-policy-but-opposed-to-nuclear-power/?_php=true&_type=blogs&_r=0

22. Morgan MG (1996) What would it take to revitalize nuclear power in the United States? *Environment* 35:7–9, 30–32.

23. International Atomic Energy Agency (2013) Small and medium sized reactors (SMRs) development, assessment and deployment. *International Atomic Energy Agency*, Vienna, Austria. Accessed March 25, 2014. Available at: http://www.iaea.org/NuclearPower/SMR/

24. Lyons PB (2013) Advancing small modular reactors: how we're supporting the next-gen nuclear energy technology. *U.S. Department of Energy.* Accessed March 25, 2014. Available at: http://energy.gov/articles/advancing-small-modular-reactors-how-were-supporting-next-gen-nuclear-energy-technology

25. International Atomic Energy Agency (2012) Status of small and medium sized reactor designs. *International Atomic Energy Agency*, Vienna, Austria, pp 34–35.

26. International Atomic Energy Agency (2012) Status of small and medium sized reactor designs. pp 72–73.

27. International Atomic Energy Agency (2012) Status of small and medium sized reactor designs. pp 28.

28. International Atomic Energy Agency (2012) Status of small and medium sized reactor designs. pp 10.

29. Lamarsh JR, Baratta AJ. (2001) *Introduction to Nuclear Engineering*. pp 164–165.

30. International Atomic Energy Agency (2014) Power reactor information system: India. *International Atomic Energy* Agency, Vienna, Austria. Accessed March 25, 2014. Available at: http://www.iaea.org/PRIS/CountryStatistics/CountryDetails.aspx?current=IN

31. International Atomic Energy Agency (2012) Status of small and medium sized reactor designs. pp 47.

32. Zhang Z, Wu Z, Wang D, Xu Y, Sun Y, Li F, Dong Y (2009) Current status and technical description of Chinese 2 x 250MW_{th} HTR-PM demonstration plant. *Nuc Eng Des* 239:1212–1219.

33. NucNet (2013) China begins construction of first generation IV HTR-PM unit. *NucNet*. Accessed March 25, 2014. Available at: http://www.nucnet.org/all-the-news/2013/01/07/china-begins-construction-of-first-generation-iv-htr-pm-unit

34. Tsvetkov PV (2011) Basic concepts of nuclear fission, in *Nuclear energy encyclopedia: science, technology, and applications*, eds Krivit SB, Lehr JH, Kingery TB (John Wiley & Sons Inc., Hoboken, NJ), pp 45–49.

35. Lamarsh JR, Baratta AJ. (2001) *Introduction to Nuclear Engineering*. pp 134.

36. International Atomic Energy Agency (2014) Power reactor information system: permanent shutdown reactors. *International Atomic Energy* Agency, Vienna, Austria. Accessed March 25, 2014. Available at: http://www.iaea.org/PRIS/WorldStatistics/ShutdownReactorsByType.aspx

37. Glaser A, Hopkins LB, Ramana MV (2013) Resource requirements and proliferation risks associated with small modular reactors. *Nucl Technol* 184(1):121–129.

38. Carelli MD, Garrone P, Locatelli G, Mancini M, Mycoff C, Trucco P, Ricotti ME (2010) Economic features of integral, modular, small-to-medium size reactors. *Prog Nucl Energy* 52:403–414.

39. McGough MS (2013) NuScale Power *Presentation to the Arizona-Mexico Commission Energy Committee*, Scottsdale, AZ. Accessed March 25, 2014. Available at: http://www.azenergy.gov/doclib/6.14.13_McGough.M_AMC_SummerPlenary_Energy.pdf

40. International Atomic Energy Agency (2012) Status of small and medium sized reactor designs. pp 56–57.

41. Mowry C (2013) Strategies for practical, economic SMR deployment. *Presentation at the Platts 3rd Annual Small Modular Reactor Conference*, Washington, D.C.

42. Rysavy CF, Rhyne SK, Shaw RP (2009) Small modular reactors. *American Bar Association*. Accessed March 25, 2014. Available at: http://apps.americanbar.org/environ/committees/nuclearpower/docs/SMR-Dec_2009.pdf

43. Halfinger J (2013) Technology update. *Presentation at the Platts 3rd Annual Small Modular Reactor Conference*, Washington, D.C.

44. Singh K (2013) SMR-160: the gravity-driven and gravity-protected, subterranean small modular reactor. *Presentation at the Platts 3rd Annual Small Modular Reactor Conference*, Washington, D.C.

45. Johnson MR (2011) Staff assessment of selected small modular reactor issues identified in SECY-10-0034. *U.S. Nuclear Regulatory Commission*, Policy Issue: SECY-11-0112. Accessed March 25, 2014. Available at: http://pbadupws.nrc.gov/docs/ML1104/ML110460434.pdf

46. Ramana MV, Hopkins LB, Glaser A (2013) Licensing small modular reactors. *Energy* 61:555–564.

47. Slovic P, Weber EU (2002) Perception of Risk Posed by Extreme Events. *Prepared for the conference: risk management strategies in an uncertain world*, Palisades, NY.

48. Slovic P, Fischhoff B, Lichtenstein S. (1982) Why Study Risk Perception? *Risk Anal* 2(2): 83–93.

49. Rosner R, Goldberg S (2011) Small modular reactors – key to future nuclear power generation in the U.S. *Energy Policy Institute at Chicago, The University of Chicago*, Chicago, IL.

50. Cooke S (2009) *In mortal hands: a cautionary history of the nuclear age* (Bloomsbury, NY).

51. Guha R (2001) *Anthropologist among the Marxists and other essays* (Universities Press, Hyderabad, India), pp 217

52. Krige J (2010) Technological leadership and American soft power, in *Soft Power and US Foreign Policy: Theoretical, historical and contemporary perspectives*, eds Parmar I, Cox M (Routledge, London), pp 121–136.

53. Hilgartner S, Bell RC, O'Connor R (1982) Nukespeak: nuclear language, visions, and mindset. (Sierra Club Books, San Francisco, CA), pp 44.

54. Hogue MT (2012) A review of the costs of nuclear power generation. *Bureau of Economic and Business Research, David Eccles School of Business* (University of Utah, Salt Lake City, UT)

55. U.S. Atomic Energy Commission (1962) Civilian nuclear power: a report to the president. *U.S. Atomic Energy Commission*, pp 34.

56. Bupp IC, Derian J (1978) *Light water: how the nuclear dream dissolved*, pp 48.

57. Bupp IC, Derian J (1978) *Light water: how the nuclear dream dissolved*, pp 49.

58. Bupp IC, Derian J (1978) *Light water: how the nuclear dream dissolved*, pp 76.

59. Schlissel DA (2008) Direct testimony of David A. Schlissel on behalf of the Maryland Public Interest Research Group Foundation, the Nuclear Information and Resource Service, Beyond Nuclear, and Public Citizen-Energy. *Public Service Commission of Maryland,* Case No: 9127. Accessed March 25, 2014. Available at: http://www.nirs.org/nukerelapse/calvert/schlisse_cc_testimony071608.pdf

60. Ramana MV (2009) Nuclear power: economic, safety, health, and environmental issues of near-term technologies. *Annu Rev Environ Resour* 34:127–152.

61. 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.

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

63. Bupp IC, Derian J (1978) *Light water: how the nuclear dream dissolved*, pp 73–74.

64. Bupp IC, Derian J (1978) *Light water: how the nuclear dream dissolved*, pp 74.

65. Brenchley F (1991) *Britain and the Middle East: economic history, 1945–1987*. (I.B.Tauris, London), pp 155–163.

66. Yeh S, Rubin ES (2012) A review of uncertainties in technology experience curves. *Energy Economics* 34:762–771.

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

68. Cooper M (2009) The economics of nuclear reactors: renaissance or relapse? *Institute for Energy and the Environment, Vermont Law School,* South Royalton, VT.

69. Kuznetsov V, Barkatullah N (2009) Approaches to assess competitiveness of small and medium sized reactors. *International Conference on Opportunities and Challenges for Water Cooled Reactors in the 21st Century*, *IAEA Paper 1S01*, *International Atomic Energy Agency*, Vienna, Austria.

70. Mulford TJ (2010) RIC 2010 regulatory and policy issues for small modular reactors (SMRs). *Presentation to the U.S. Nuclear Regulatory Commission*, Rockville, Maryland.

71. Hastie R, Dawes R (2010) *Rational choice in an uncertain world: the psychology of judgment and decision making* (Sage, Los Angeles CA).

72. Henrion M, Fischhoff B (1986) Assessing uncertainty in physical constants. *American Journal of Physics* 54:791-798.

73. Raiffa H, Schlaifer R (1961) *Applied statistical decision theory*, (Harvard University, Cambridge MA).

74. Howard RA, Matheson JE (eds) (1984) *The principles and applications of decision analysis*, (Strategic Decisions Group, Menlo Park, CA).

75. Keeney RL (1982) Decision analysis: An overview. *Oper Res* 30: 803-837.

76. Watson SR, Buede DM (1987) *Decision synthesis: The principles and practice of decision analysis* (Cambridge Univ Press, New York).

77. von Winterfeldt D, Edwards W (1986) *Decision analysis and behavioral research* (Cambridge Univ Press, New York).

78. Spetzler CS, Staël von Holstein C-AS (1975) Probability encoding in decision analysis. *Management Science* 22:340–352.

79. Morgan MG, Henrion M (1990) *Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis* (Cambridge Univ Press, Cambridge, New York).

80. Hetes B et al. (2011) *EPA expert elicitation task force white paper* (U.S. EPA, Washington D.C.). Available at: www.epa.gov/stpc/pdfs/ee-white-paper-final.pdf

81. Morgan MG, Keith D (1995) Subjective judgments by climate experts. *Environ Sci Technol* 29: 468A–476A.

82. Morgan MG, Adams P, Keith D (2006) Elicitation of expert judgments of aerosol forcing. *Clim Change* 75:195–214.

83. Zickfeld K, Levermann A, Kuhlbrodt T, Rahmstorf S, Morgan MG, Keith D (2007) Expert judgments on the response on the atlantic meridional overturning circulation to climate change, *Clim Change* 82:235–265.

84. Zickfeld K, Morgan MG, Frame D, Keith D (2010) Expert judgments about transient climate response to alternative future trajectories of radiative forcing. *Proc Natl Acad Sci USA* 107:12451–12456

85. Morgan MG, Pitelka LP, Shevliakova E (2001) Elicitation of expert judgments of climate change impacts on forest ecosystems. *Clim Change* 49: 279–307.

86. Morgan MG, Morris SC, Meier AK, Shenk DL (1978) A probabilistic methodology for estimating air pollution health effects from coal-fired power plants. *Energy Systems and Policy* 2: 287–310.

87. Roman HA, Walker KD, Walsh TL, Conner L, Richmond HM, Hubbell BJ, Kinney P (2008) Expert judgment assessment of the mortality impact of changes in ambient fine particulate matter in the U.S. *Environ Sci Technol* 42: 2268–2274.

88. Tversky A, Kahneman D (1974) Judgment under uncertainty: heuristics and biases. *Science* 185:1124–1131.

89. Kahneman D, Slovic P, Tversky A, eds. (1982) *Judgment under uncertainty: Heuristics and biases* (Cambridge Univ Press, New York).

90. Kahneman D (2011) *Thinking fast and slow* (Farrar, Straus and Giroux, New York).

91. Curtright A, Morgan MG, Keith D (2008) Expert assessment of future technology. *Environ Sci Technol* 42(24):9031–9038.

92. Zhang Z, Sun Y (2007) Economic potential of modular reactor nuclear power plants based on the Chinese HTR-PM project. *Nuc Eng Des* 237:2265–2274.

93. Reyes JN (2011) Overview of NuScale technology. *Presentation to the International Atomic Energy Agency*, Vienna, Austria.

94. Anness M (2011) Westinghouse SMR product development. *Presentation to the International Atomic Energy Agency*, Vienna, Austria.

95. International Atomic Energy Agency (2000) Economic evaluation of bids for nuclear power plants 1999 edition. *IAEA Technical Report Series No. 396, International Atomic Energy Agency,* Vienna, Austria.

96. Energy Information Administration (2010) Updated capital cost estimates for electricity generation plants. *Office of Energy Analysis, U.S. Department of Energy,* Washington, D.C.

97. Conditions of licenses (2012) *U.S. Code of Federal Regulations*, *Title 10, section 50.54.m.2.i.*

98. Anton S (2011) HI-SMUR 140. *Presentation to the U.S. Nuclear Regulatory Commission*, Washington, D.C.

99. Kim TJ (2010) Generation mPower. *Presentation to the American Nuclear Society*, Washington, D.C.

100. Ingersoll DT (2009) Deliberately small reactors and the second nuclear era. *Prog Nucl Energy* 51:589–603.

101. Solan D et al. (2010) Economic and employment impacts of small modular nuclear reactors. *Energy Policy Institute*, *Boise State University*, Boise, ID.

102. 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.

103. Nuclear Energy Agency (2011) Current status, technical feasibility, and economics of small nuclear reactors. *Nuclear Energy Agency*, Paris, France.

104. Cunningham N (2012) Small modular reactors: A possible path forward for nuclear power. *American Security Project*, Washington, DC.

105. Black G (2012) Estimating the economic impacts of small modular reactors. *Presentation to the Platts 3rd Annual Small Modular Reactors Conference,* Arlington, VA.

106. Wagner SJ, Rubin ES (2012) Economic implications of thermal energy storage for concentrate solar thermal power. *Renew Energy* 61:81–95.

107. Kammen DM, Pacca S (2004) Assessing the costs of electricity. *Annu Rev Environ Resour* 29:301–344.

108. Ansolabehere S, Deutch J, Driscoll M, Gray PE, Holdren JP, Joskow PL, Lester RK, Moniz EJ, Todreas NE (2003) *The future of nuclear power* (Massachusetts Institute of Technology, Cambridge, MA).

109. Du Y, Parsons JE (2009) *Update on the cost of nuclear power* (Massachusetts Institute of Technology, Cambridge, MA).

110. Nuclear Energy Institute (2011) Costs: Fuel, operation and waste disposal. *Nuclear Energy Institute*, Washington, D.C. Accessed March 25, 2014. Available at: http://www.nei.org/resourcesandstats/nuclear_statistics/costs

111. Energy Information Administration (2012) Levelized cost of new generation resources in the Annual Energy Outlook 2012. *Officer of Energy Analysis, U.S. Department of Energy*, Washington, D.C. Accessed March 25, 2014. Available at: http://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf

112. Energy Information Administration (2014) Electricity wholesale market data*. U.S. Department of Energy.* Accessed April 22, 2014. Available at: http://www.eia.gov/electricity/wholesale/

113. Anadon LD, Bosetti V, Bunn M, Catenacci M, Lee A (2012) Expert judgments about RD&D and the future of nuclear energy. *Environ Sci Technol* 46(21):11497–11504

114. Ueckerdt F, Hirth L, Luderer G, Edenhofer O (2013) System LCOE: What are the costs of variable renewables? *Potsdam Institute for Climate Impact Research*, Potsdam, Germany.

115. Katzenstein W, Apt J (2012) The Cost of Wind Power Variability. *Energy Policy* 51:233–243.

116. International Atomic Energy Agency (2013) Nuclear power reactors in the world. Tables 1 and 5.

117. International Atomic Energy Agency (2006) Viability of inert matrix fuel in reducing plutonium amounts in reactors. *International Atomic Energy Agency (IAEA-TECDOC-1516)*, Vienna, Austria.

118. International Atomic Energy Agency (2010) Small reactors without on-site refueling: Neutronic characteristics, emergency planning and development scenarios. *International Atomic Energy Agency (IAEA-TECDOC-1652)*, Vienna, Austria.

119. Schleicher R, Back C (2012) Configuring EM^2 to meet the challenges of economics, waste disposition and non-proliferation confronting nuclear energy in the U.S. *Transactions of Fusion Science and Technology* 61:144–149

120. Smith-Kevern R (2013) Small modular reactors. *Presentation to the U.S. Nuclear Regulatory Commission*. Accessed March 26, 2014. Available at:

http://www.nrc.gov/reading-rm/doc-collections/commission/slides/2013/20130422/smith-kevern-smr-slides-20130422.pdf

121. Halfinger JA, Hagherty MD (2012) The B&W mPower scalable practical nuclear reactor design. *Nuclear Technology* 178:164.

122. Generation mPower (2011) Technology > deployment. *Generation mPower*. Accessed March 26, 2014. Available at: http://www.generationmpower.com/technology/deployment.asp

123. Roulstone T (2013) Russia's floating nuclear plants to power remote Arctic regions. *The Conversation*. Accessed March 26, 2014. Available at: http://theconversation.com/russias-floating-nuclear-plants-to-power-remote-arctic-regions-19994

124. Fadeev Y (2011) KLT-40S reactor plant for the floating CNPP FPU. *Presentation to the International Atomic Energy Agency*. Accessed March 26, 2014. Available at: http://www.iaea.org/NuclearPower/Downloads/Technology/meetings/2011-Jul-4-8-ANRT-WS/2_%D0%9ALT-40S_VBER_OKBM_Afrikantov_Fadeev.pdf

125. International Atomic Energy Agency (2013) Update on KLT-40S. *International Atomic Energy Agency*. Accessed March 26, 2014. Available at: http://www.iaea.org/NuclearPower/Downloadable/aris/2013/25.KLT-40S.pdf

126. International Atomic Energy Agency (2013) Status of innovative fast reactor designs and concepts. *International Atomic Energy Agency*, Vienna, Austria, pp 19–20.

127. Ishii K, Matsumiya H, Handa N (2011) Activities for 4S USNRC licensing. *Prog Nucl Energy* 53:831–834.

128. International Atomic Energy Agency (2011) Status report 96 – high temperature gas cooled reactor – pebble-bed module (HTR-PM). *International Atomic Energy Agency*.

129. Zrodnikov AV, Toshinsky GI, Komlev OG, Stepanov VS, Klimov NN (2011) SVBR-100 module-type fast reactor of the IV generation for regional power industry. *J Nucl Mater* 415(3):237–244.

130. General Atomics (2013) EM^2 quick facts. *General Atomics*. Accessed March 26, 2014. Available at: http://www.ga.com/websites/ga/docs/em2/pdf/FactSheet_QuickFactsEM2.pdf

131. World Nuclear Association (2013) Nuclear fuel fabrication. *World Nuclear Association*. Accessed March 26, 2014. Available at: http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Conversion-Enrichment-and-Fabrication/Fuel-Fabrication/

132. Krass AS, Boskma P, Elzen B, Smit WA (1983) *Uranium enrichment and nuclear weapon proliferation* (Taylor & Francis Ltd, London).

133. Wood HG, Glaser A, Kemp RS (2008) The gas centrifuge and nuclear weapons proliferation. *Phys Today* 61(9):40–45.

134. Bush GW (2004) Remarks by the President on Weapons of Mass Destruction Proliferation. *National Defense University*, Washington D.C.

135. Nuclear Threat Initiative (2014) Civilian uses of HEU. *Nuclear Threat Initiative*. Accessed March 26, 2014. Available at: http://www.nti.org/analysis/articles/civilian-uses-heu/

136. National Nuclear Security Administration (2001) Highly enriched uranium: striking a balance. *U.S. Department of Energy*, Washington, D.C., appendix D.

137. Reistad O, Ølgaard PL (2006) Russian nuclear power plants for marine applications. *Nordisk kernesikkerhedsforskning (Nordic nuclear safety research)*, NKS–138.

138. Federation of American Scientists (2000) Project 705 Lira. *Federation of American Scientists*. Accessed March 26, 2014. Available at: https://www.fas.org/man/dod-101/sys/ship/row/rus/705.htm

139. Pinkus B, Tlamim M (2002) Atomic power to Israel's rescue: French-Israeli nuclear cooperation, 1949–1957 *Israel Stud* 7(1):104–138.

140. Cohen A (1999) *Israel and the bomb* (Columbia Univ Press, NY).

141. Hersh S (1993) *The Samson option: Israel's nuclear arsenal and American foreign policy* (Vintage, NY).

142. Mian Z, Nayyar AH, Rajaraman R, Ramana MV (2006) Fissile materials in South Asia: The implications of the U.S.-India nuclear deal. *A research report of the International Panel on Fissile Materials*.

143. Abraham I (1998) *Making of the Indian atomic bomb: Science, secrecy and the postcolonial state* (Zed Books, London).

144. Nuclear Threat Initiative, Rajasthan atomic power station (RAPS). *Nuclear Threat Initiative*. Accessed March 26, 2014. Available at: http://www.nti.org/facilities/76/

145. Huang L, Zhou Y, Han Y, Hammitt JK, Bi J, Liu Y (2013) Effects of the Fukushima nuclear accident on the risk perception of residents near a nuclear power plant in China. *Proc Natl Acad Sci USA* 110(49):19742–19747.

146. Weinberg AM (1972) Social institutions and nuclear energy. *Science* 177:27–34.

147. American Security Project (2013) American security enhanced: the benefits of the New START Treaty. *American Security Project.*

148. BBC News (2001) America withdraws from ABM treaty. *British Broadcasting Corporation*. Accessed March 26, 2014. Available at: http://news.bbc.co.uk/2/hi/americas/1707812.stm

149. Toki M (2014) Heavy lifting ahead in the Japan-India nuclear deal. *Bulletin of the Atomic Scientists.* Accessed March 26, 2014. Available at: http://thebulletin.org/heavy-lifting-ahead-japan-india-nuclear-deal

150. Paul TV (2000) *Power versus prudence: why nations forgo nuclear weapons* (McGill-Queen's Univ Press, Montreal, Canada).

151. Reiss M (1994) *Bridled ambition: why countries constrain their nuclear capabilities* (Woodrow Wilson Center Press, Washington, D.C.).

152. Nuclear Threat Initiative (2013) Nuclear disarmament resource collection. *Nuclear Threat Initiative.* Accessed March 26, 2014. Available at: http://www.nti.org/analysis/reports/nuclear-disarmament/

153. Treaty for the Prohibition of Nuclear Weapons in Latin America and the Caribbean (1968) *The Agency for the Prohibition of Nuclear Weapons in Latin America and the Caribbean*. Accessed March 26, 2014. Available at: http://www.opanal.org/opanal/Tlatelolco/Tlatelolco-i.htm

154. Shultz GP, Perry WJ, Kissinger HA, Nunn S (2008) Toward a nuclear-free world. *Wall Street Journal*.

155. Wilson, W (2013) Rethinking the utility of nuclear weapons. *Parameters* 42(4)/43(1):35–39.

156. Panofsky WKH (2007) Nuclear insecurity. *Foreign Affairs* 86(5). Accessed March 26, 2014. Available at: http://www.foreignaffairs.com/articles/62832/wolfgang-k-h-panofsky/nuclear-insecurity

157. Mecklin J (2012) The German nuclear exit: Introduction. *Bulletin of the Atomic Scientists* 68:6–9.

158. Schreurs MA (2012) The politics of phase-out. *Bulletin of the Atomic Scientists* 68:30–41.

159. U.S. Nuclear Regulatory Commission (2012) Fact sheet on nuclear insurance and disaster relief funds. *U.S. Nuclear Regulatory Commission*.

160. Benedict K (2013) Are small nuclear reactors the answer? *Bulletin of the Atomic Scientists*. Accessed March 26, 2014. Available at: http://thebulletin.org/are-small-nuclear-reactors-answer

161. Myhre JC (2001) Electrical power supply to offshore oil installations by high voltage direct current transmission. *Norwegian University of Science and Technology.* Ph.D. dissertation.

162. Bogan J (2008) Shell's radical rig. *Forbes Magazine*. Accessed March 27, 2014. Available at: http://www.forbes.com/forbes/2008/1124/072.html

163. Lieber R (2000) Life on board a Gulf of Mexico oil drilling platform. *Fast Company*. Accessed March 27, 2014. Available at: http://www.fastcompany.com/41051/life-board-gulf-mexico-oil-drilling-platform

164. NuScale Power (2013) Changing the face of energy. *NuScale Power*. Accessed March 27, 2014. Available at: http://www.nuscalepower.com/pdf/nuscale-brochure-2013.pdf.

165. Chevron (2009) Major capital project: Tahiti. *Deepwater Exploration and Project Business Unit*. Accessed March 27, 2014. Available at: http://www.chevron.com/documents/pdf/pressreleases/tahitifactsheet.pdf

166. Davies J (2014) Standardizing the international nuclear community: Lessons learnt from the aerospace industry. *Nuclear Energy Insider*.

167. Goodman D, Raetzke C (2013) SMRs: The vehicle for an international licensing framework? A possible model. *Proceedings of ICAPP 2013*. Paper No.: FA075.

168. XE Currency Converter (2014) IMF special drawing rights to US dollar rate. *XE Currency Converter*. Rate: 1.00XDR = 1.54USD. Accessed March 27, 2014. Available at: http://www.xe.com/currencyconverter/convert/?From=XDR&To=USD

169. Gold Price Oz (2014) Gold prices per ounce today. *Gold Price Oz*. Price: $1297.9/oz. Accessed March 27, 2014. Available at: http://www.goldpriceoz.com/gold-price-per-ounce/

170. Burns SG (2013) A perspective from Paris: Modernizing the nuclear liability regimes. *Presentation at the 5th Annual NEI-Pillsbury Seminar: Hot Button Issues in International Nuclear Trade and Investment*, Washington, D.C.

171. Truelove HB (2012) Energy source perceptions and policy support: Image associations, emotional evaluations, and cognitive beliefs. *Energy Policy* 45:478–489.

172. Bickerstaff K, Lorenzoni I, Pidgeon NF, Poortinga W, Simmons P (2008) Reframing nuclear power in the UK energy debate: nuclear power, climate change mitigation and radioactive waste. *Public Underst Sci* 17:145–169.

173. Corner A, Venables D, Spence A, Poortinga W, Demski C, Pidgeon NF (2011) Nuclear power, climate change and energy security: Exploring British public attitudes. *Energy Policy* 39:4823–4833.

174. Doyle J (2011) Acclimatizing nuclear? Climate change, nuclear power and the reframing of risk in the UK news media. *International Communication Gazette* 73:107–125.

Appendix A

Expert elicitation protocol

Elicitation of Expert Assessments of Small Modular Reactor Costs

Interview Protocol

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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.

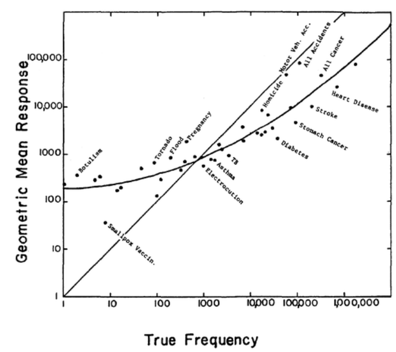
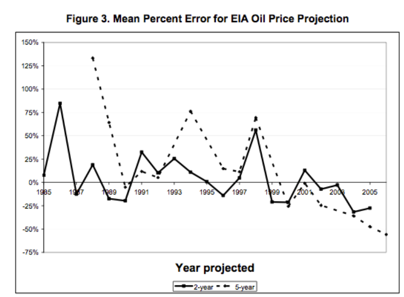


Figure demonstrating the availability heuristic. From Lichtenstein et al. (1978)



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:

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This graphic is under copyright.

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

This graphic is under copyright.

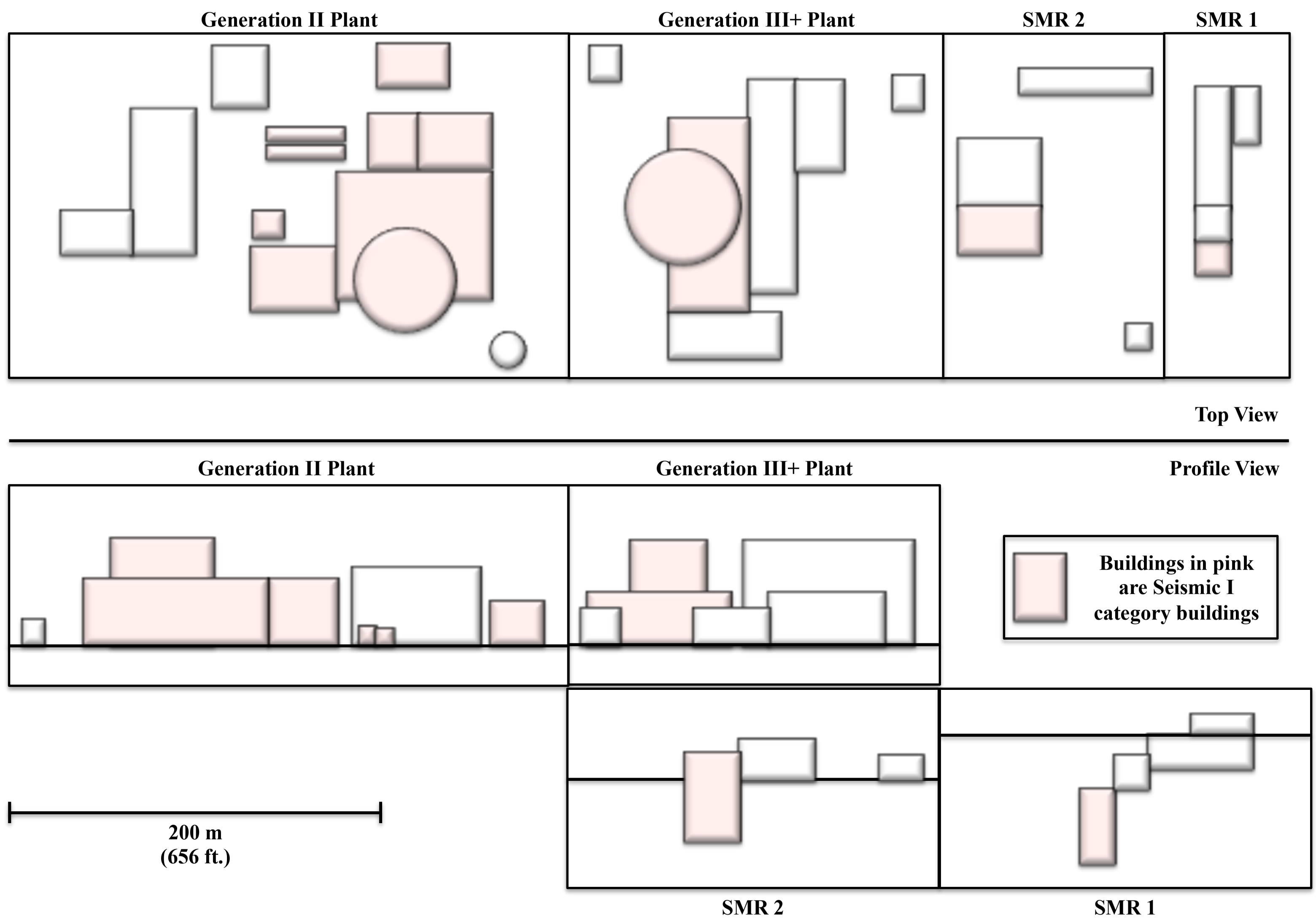
This graphic is under copyright.

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.

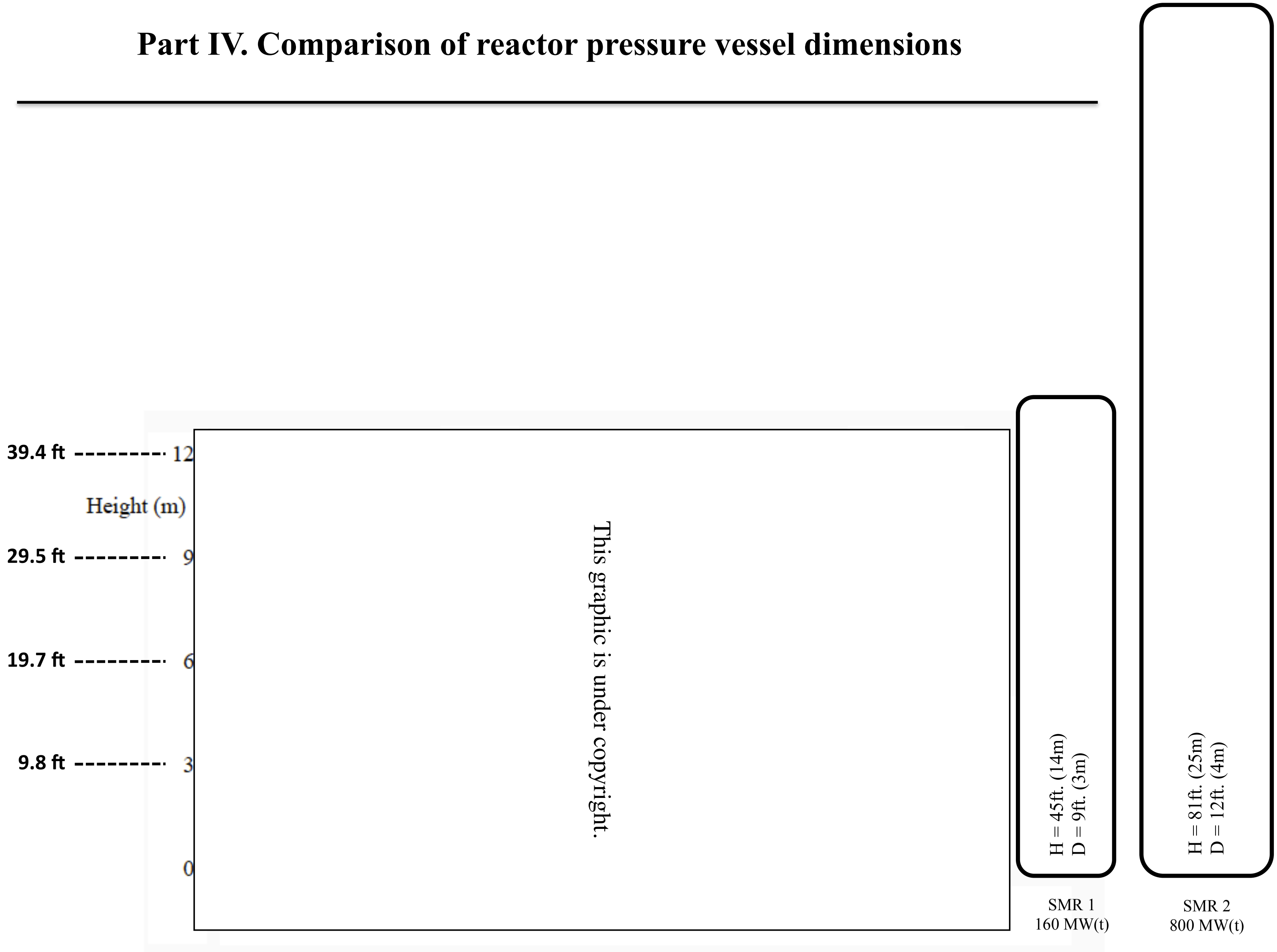
We shall call this design SMR Number 2

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



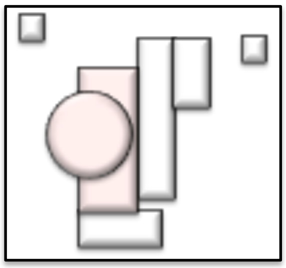
Page 8

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

Scenario 1

Plant with 1 GenIII+ conventional reactor

1,000 MWe



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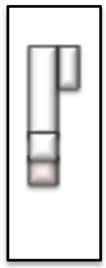
Scenario 2

Plant with 1 x SMR 1

45 MWe



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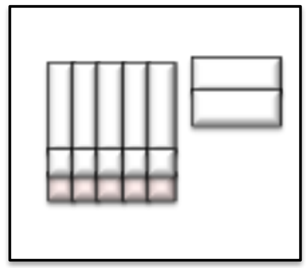
Scenario 3

Plant with 5 x SMR 1

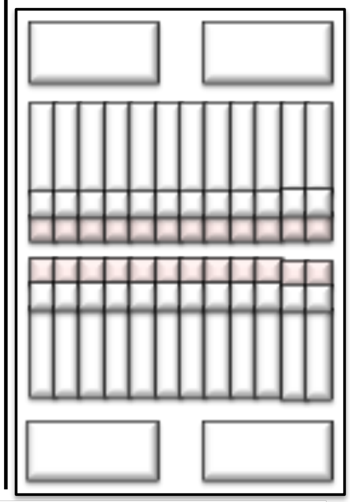
225 MWe



Scenario 4

Plant with 24 x SMR 1

1,080 MWe



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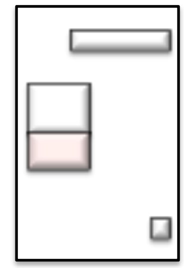
Scenario 5

Plant with 1 x SMR 2

225 MWe



This graphic is under copyright.

Buildings in pink are Seismic I category buildings

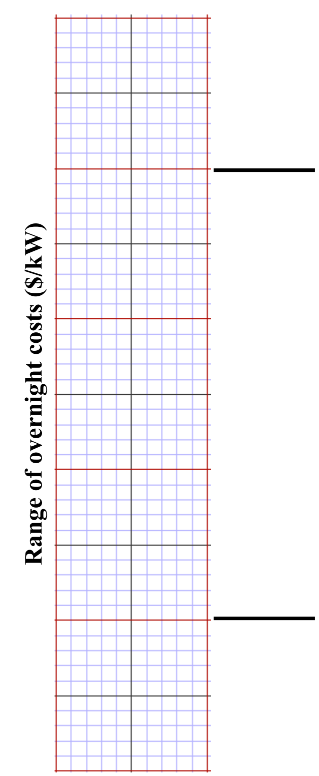
Scenario 1: the picture at the top is from the Institute for Southern Studies (http://www.southernstudies.org/images/sitepieces/AP1000Reactor.jpg), and the picture at the bottom is from the IAEA (http://aris.iaea.org/sonar/image/p00179_image016.jpg). Scenarios 2 through 4: the pictures are from the the 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



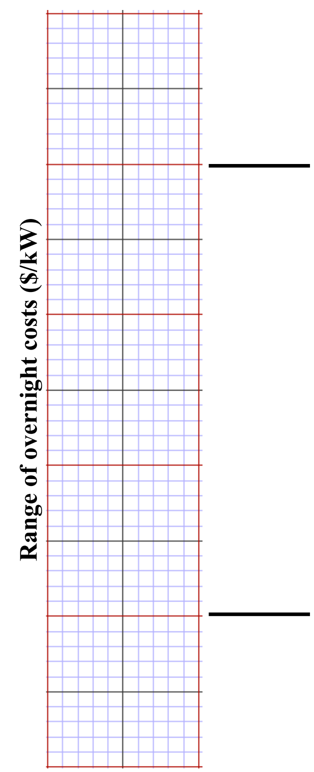
Part V. Eliciting overnight costs – conventional reactor plant

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

Plant with 1 x SMR 1

45 MWe

Range of overnight costs ($/kW)

Scenario 3

Plant with 5 x SMR 1

225 MWe

Range of overnight costs ($/kW)

Scenario 4

Plant with 24 x SMR 1

1,080 MWe

Range of overnight costs ($/kW)

Scenario 5

Plant with 1 x SMR 2

225 MWe

Range of overnight costs ($/kW)

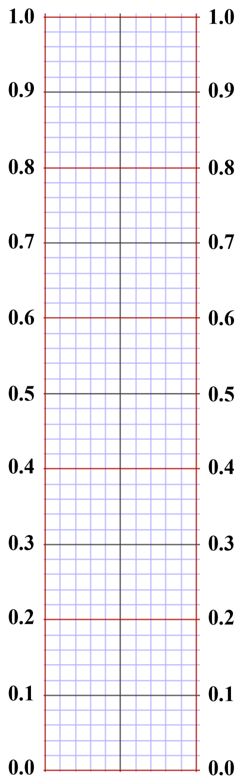
Part V. Probability of scenarios achieving a target cost - 1

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

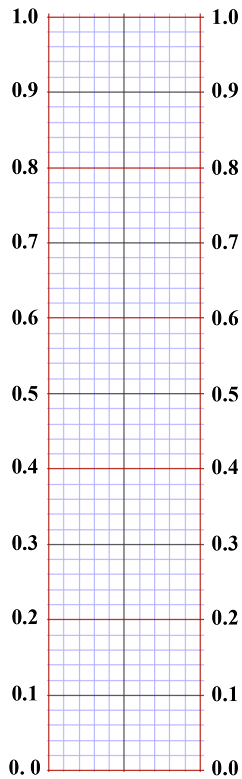
1,000 MWe



Scenario 2

Plant with 1 x SMR 1

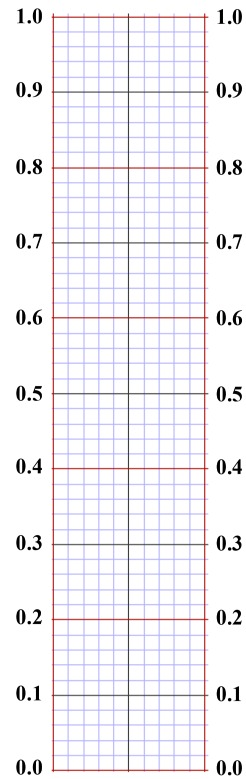
45 MWe



Scenario 3

Plant with 5 x SMR 1

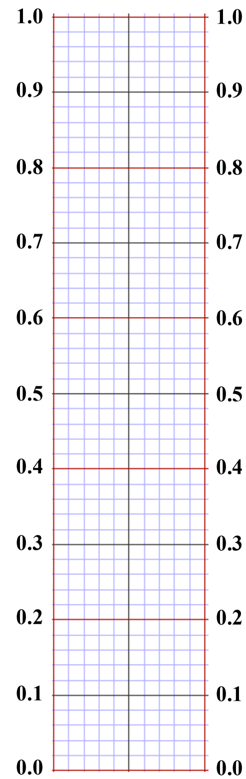
225 MWe



Scenario 4

Plant with 24 x SMR 1

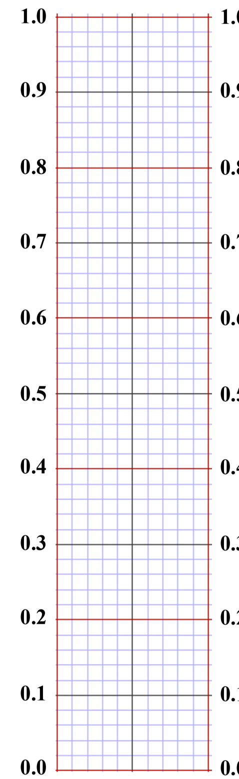
1,080 MWe



Scenario 5

Plant with 1 x SMR 2

225 MWe



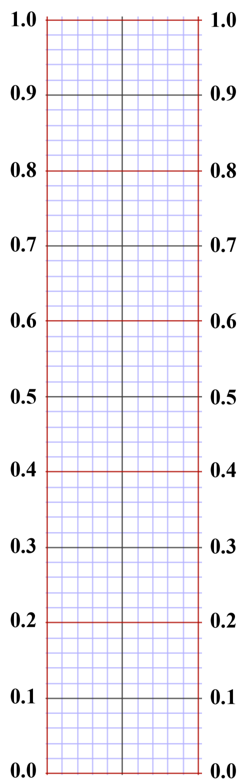
Part V. Probability of scenarios achieving a target cost - 2

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

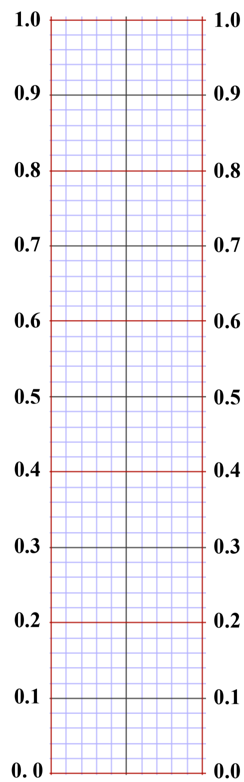
1,000 MWe



Scenario 2

Plant with 1 x SMR 1

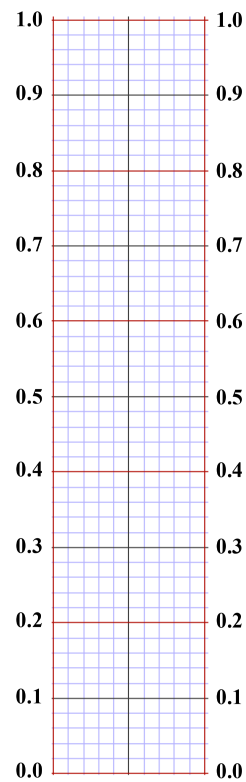
45 MWe



Scenario 3

Plant with 5 x SMR 1

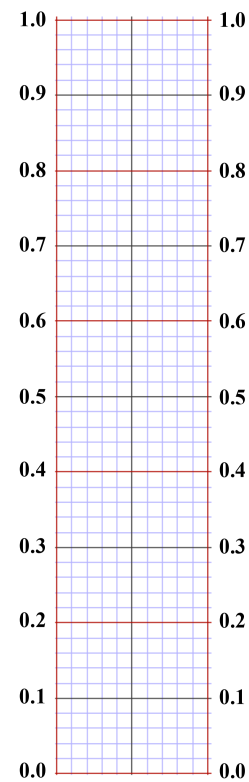
225 MWe



Scenario 4

Plant with 24 x SMR 1

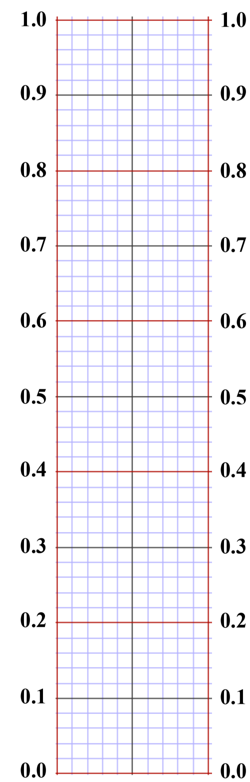
1,080 MWe



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	☐	______

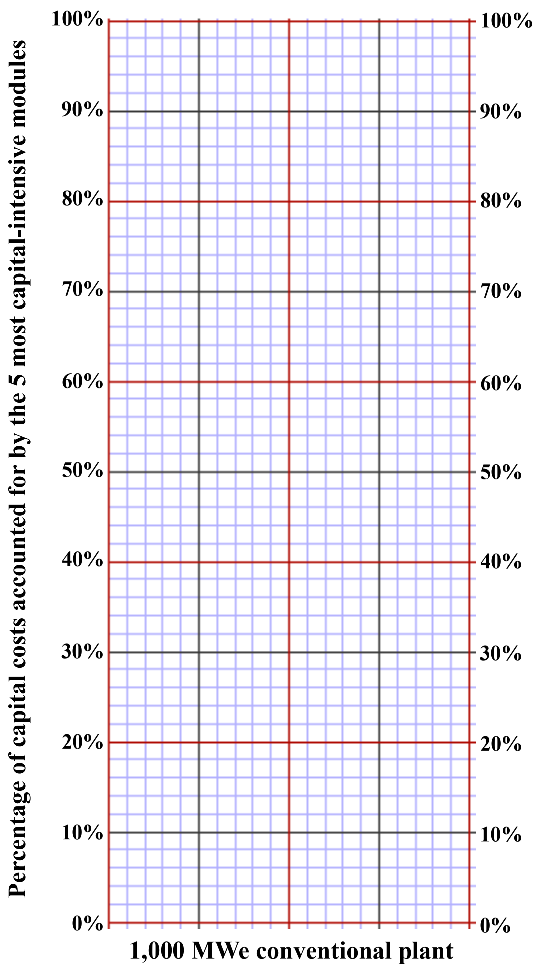
Part VI. Ranking SMR plant modules under consideration

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).

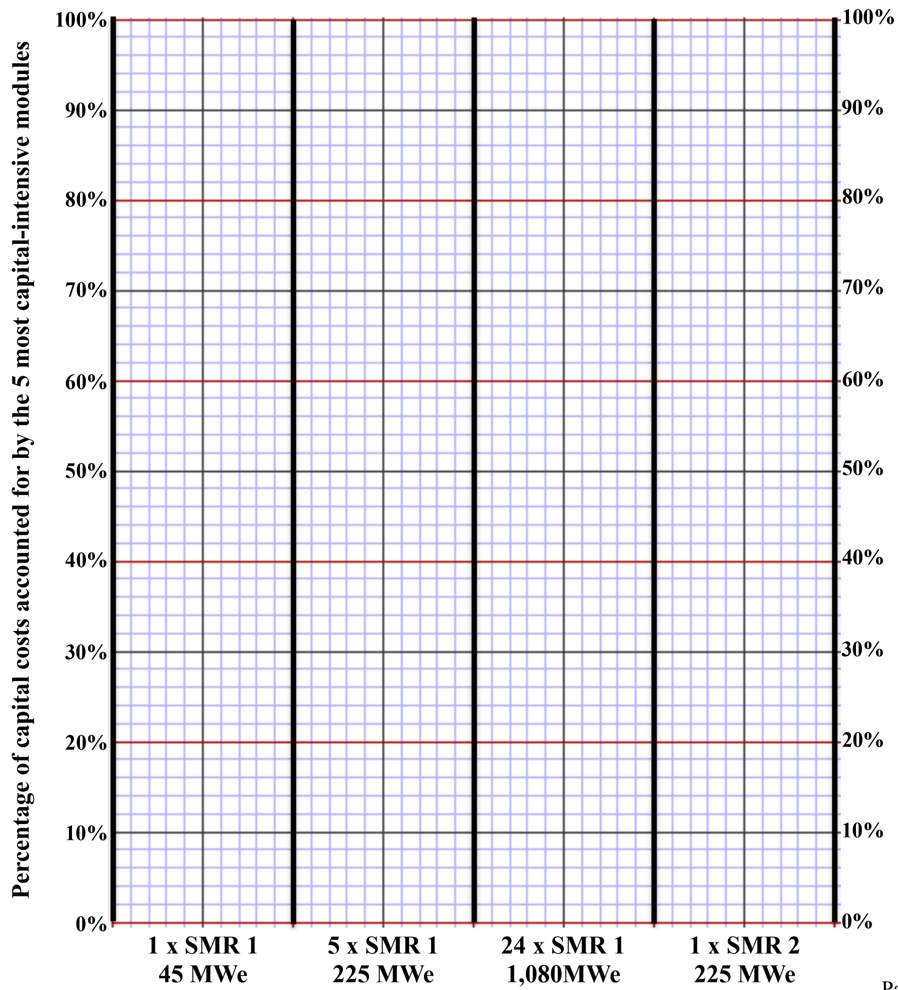
We divide a nuclear power plant into the following modules:	*Rank*	*Do you foresee any of the modules being irrelevant for SMRs? Would you suggest we ignore some of the modules listed?*
Building and site preparation	☐	☐
Reactor plant equipment	☐	☐
Turbine plant equipment	☐	☐
Generator plant equipment	☐	☐
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?

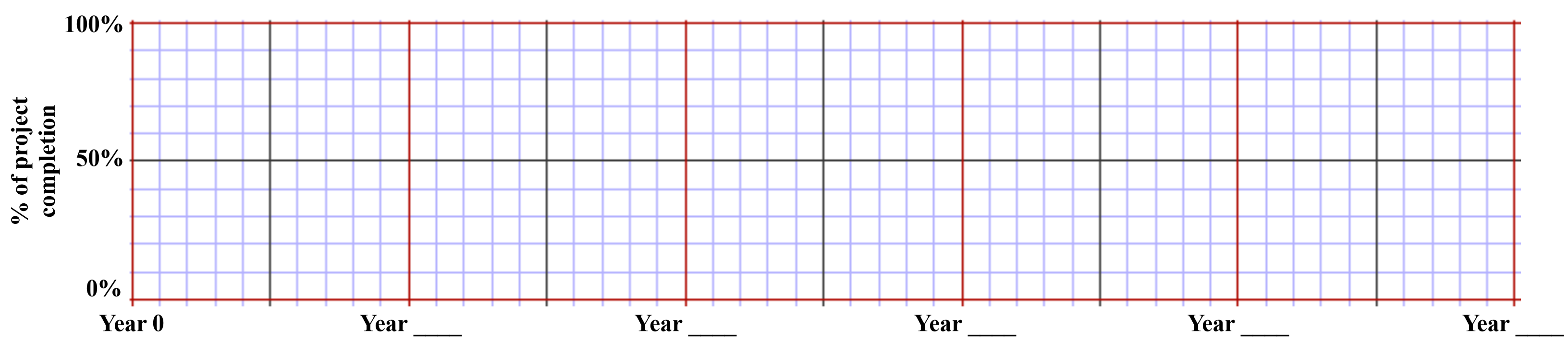
In the literature, authors scale gross capital costs by reactor capacity. We would now like to explore this approach to determining SMR plant capital costs. For a first attempt at a top-down cost estimate, is it fair to assume that some of the costs associated with a plant operating SMRs are scalable 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.

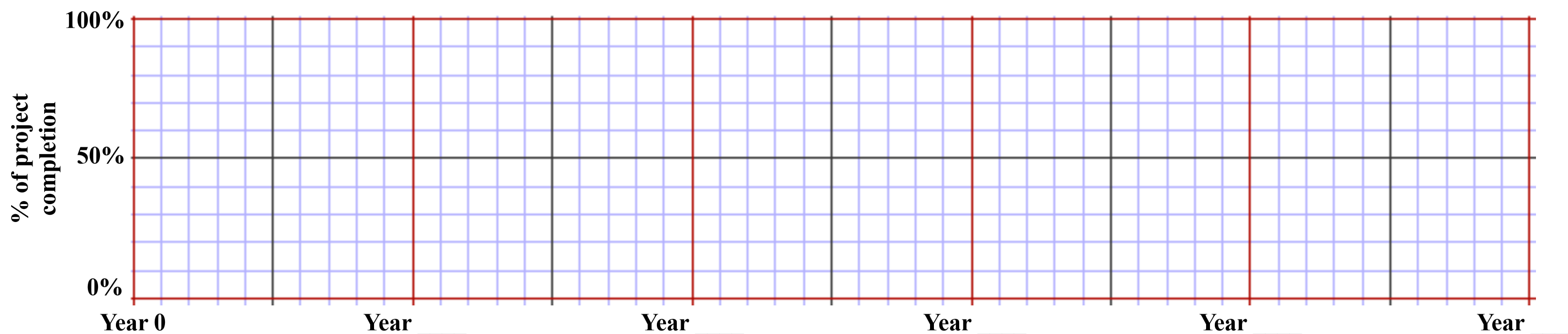
Scenario 0 **Demonstration**



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?

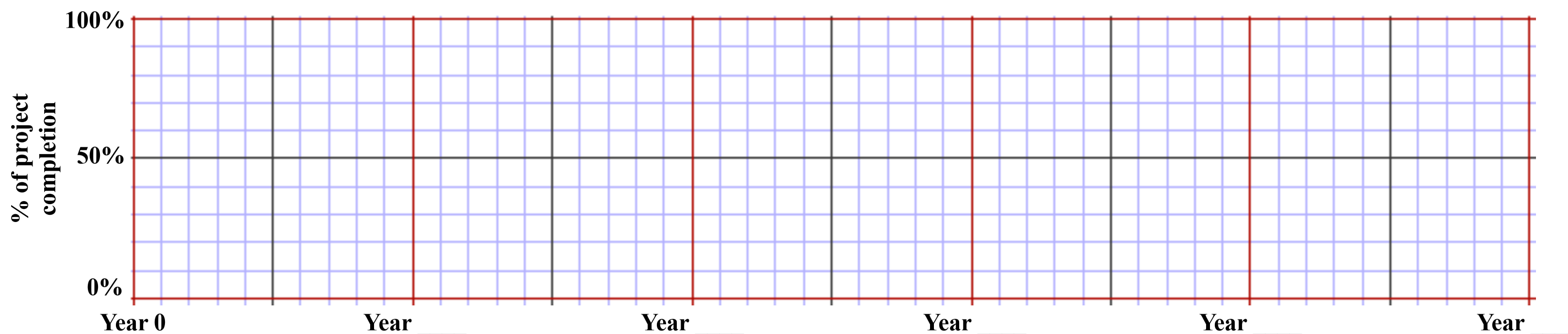
Scenario 1 **Plant with 1 GenIII+ conventional reactor** **1,000 MWe**



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?

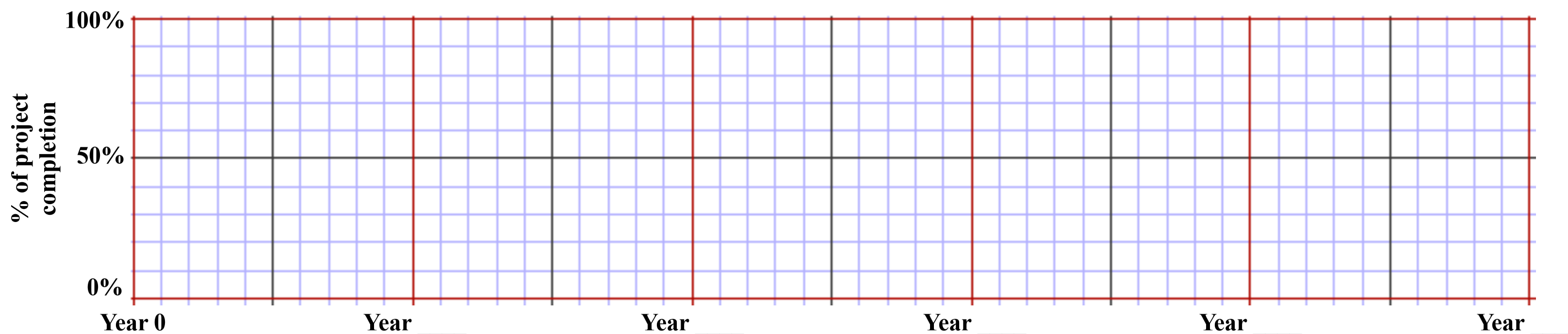
Scenario 2 **Plant with 1 x SMR 1** **45 MWe**



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?

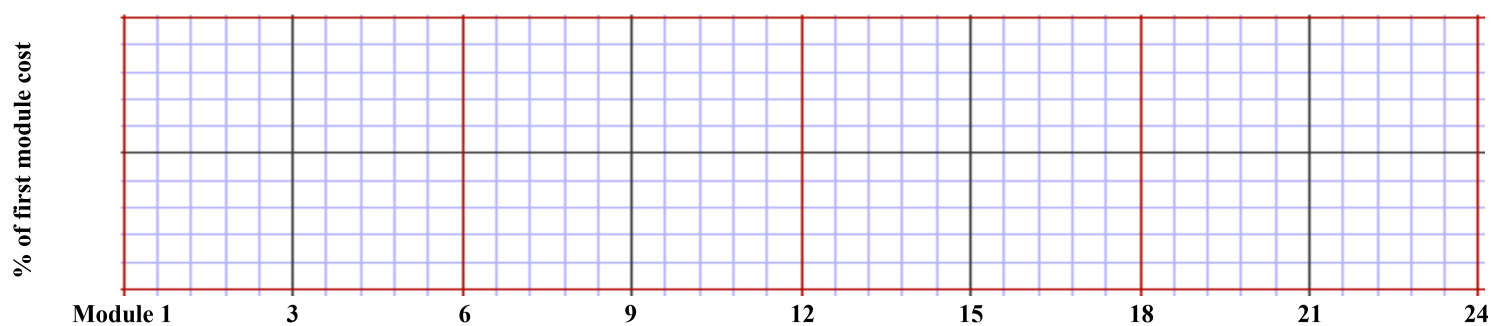
Scenario 5	Plant with 1 x SMR 2	225 MWe



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**



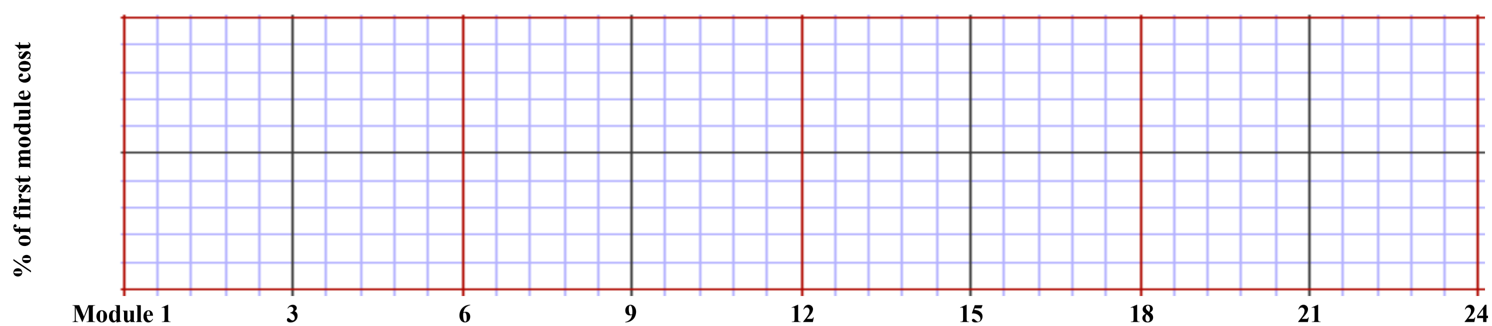
When answering this question, please do the following:

(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**

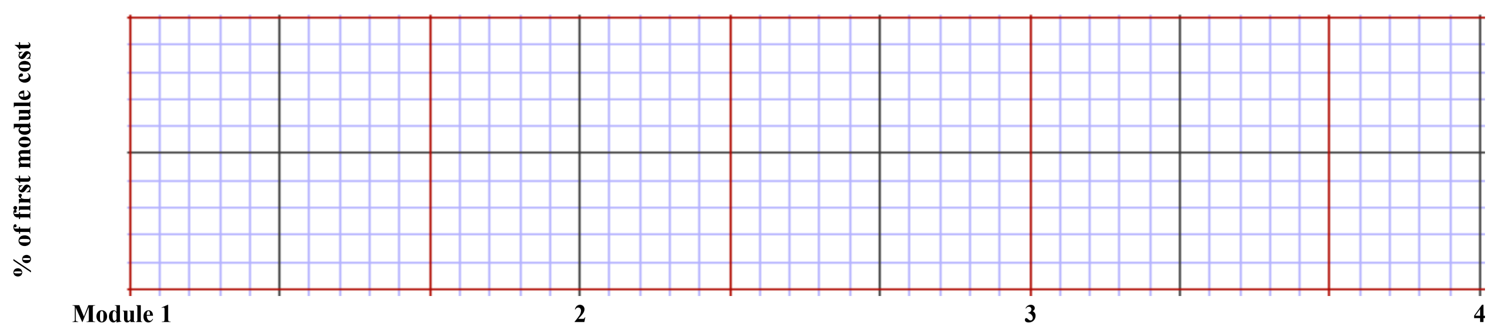


When answering this question, please do the following:
(1) Place a dot where you think the first module would be on the y-axis (at module 1)
(2) Draw the curve that corresponds to your estimate of modularity's influence on the capital cost of subsequent modules installed at the same site.

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**



When answering this question, please do the following:
(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.

This graphic is under copyright.

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.

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*

Appendix B

Workshop booklet and materials

Participant Name (please print): ___________________________________

Workbook for:

A Workshop on Small Modular Reactors (SMRs)

Implications of SMRs on low carbon energy and nuclear security

Hosted by

Carnegie Mellon University, Pittsburgh PA, U.S.A.
The Paul Scherrer Institut, Villigen, Switzerland
The International Risk Governance Council, Lausanne, Switzerland

Thank you for agreeing to participate in our workshop. We have set up a web site to which we have uploaded electronic versions of the workshop agenda, logistical details, and some readings that might be relevant to our discussion. Please direct your browser to the following address to access these materials:

http://www.epp.cmu.edu/SMR

This workbook contains the response sheets for the various exercises that you will be asked to complete over the next two days.

We will be collecting this workbook at the end of the workshop. We will send an anonymous summary of everyone's responses back to you as soon as we have compiled them after the workshop. Once the information has been further synthesized and a review paper summarizing our collective views has been produced, we will share a draft with all participants before making it publicly available.

The entire workshop is being held under the ***Chatham House rule****, by which we mean that the content of the discussions and the assessments that participants provide will not be attributed to them without their explicit permission.*

Participants are asked to draw upon their expertise and judgment when answering the questions as individual experts. In other words, we are not asking you to represent the organization you are affiliated with.

Support for this event has been provided by The John D. and Catherine T. MacArthur Foundation, the International Risk Governance Council, the Paul Scherrer Institut, the EPFL Center on Risk Analysis and Governance, and the Center for Climate and Energy Decision Making at Carnegie Mellon University, which is supported by the U.S. National Science Foundation.

Session 1: Assessment of SMR advantages and economic viability

Session chair: M. Granger Morgan, Carnegie Mellon University

08:45 – 09:00 Kick-off exercise:Proposed SMR designs incorporate a number of characteristics that are intended to promote their adoption and reduce the risks associated with nuclear power plant deployment.

Each workshop participant will receive two **identical** decks of cards. These list 15 factors that could help advance the adoption of SMRs. In mid-October, we sent you an e-mail asking you to think of and share 3 characteristics of SMRs that, in your judgment,most helppromote the adoption of these reactors. We used those as input developing the content of these cards.

Assuming that the market has grown sufficiently in size to allow for the manufacturing of one or more SMR designs in dedicated factories (as opposed to stick-build, on-site construction), and that while cost per kW_e might still be higher, total capital expenditure will be substantially lower than for much larger, conventional reactors:

Question 1. Please choose the **FIVE** factors that you believe will most help promote the adoption of SMRs in OECD countries. Give the highest rank to the factor you believe most contributes to the promotion of SMRs. Record your order on the cards themselves.

Please remember to record your rankings on the cards.

Question 2. Please turn your attention to the second deck of cards now. Choose the **FIVE** factors that you believe will most help promote the adoption of SMRs in developing countries. Give the highest rank to the factor you believe most contributes to the promotion of SMRs. Record your order on the cards themselves.

Again, please remember to record your rankings on the cards.

09:00 – 09:20 We will now briefly discuss the challenges that will have to be addressed by the nuclear industry if SMRs are to become viable competitors to existing forms of energy generation.

Question 3. Lowering cost of manufacturing: What is the probability that an SMR design will be available in 20 years with an overnight manufacturing cost (in $/installed capacity) that is…

…**the same as, or lower than**, that of current large Gen III+ reactors? (Please mark an X on the scale below):

0	0.33	0.66	1
No chance it will happen.			Definitely it will happen.

…**at least 20% lower than** the current cost of large Gen III+ reactors?

0	0.33	0.66	1
No chance it will happen.			Definitely it will happen.

What do you see as the largest obstacles to lowering the manufacturing costs of SMRs so that they are as low or lower than the cost of conventional reactors?

As you know, lowering the cost of manufacturing is not the only challenge facing SMR designs.

On the next page welist some additional challenges faced by SMRs, and we will ask you to judge how crucialresolving each one is.

Successful SMRs will be those that complete the journey from conceptual design to mass deployment. On the next page, we have listed a number of the major milestones in this journey. We understand that the flow from one milestone to the next is not sequential, and that a few of these can be pursued in parallel.

Question 4. How would you rate the difficulty of each of these steps? How crucial is the resolution of each to the general health of the industry? It might be useful to start with the most difficult step, since this analysis is necessarily comparative.

	How difficult will achieving each step be? (Please mark an X on each scale below)	How urgently must each be resolved for SMRs to become a viable energy alternative?(Mark an X on each scale below)
Finalize a design control document for a particular reactor system	0 1 2 3 4 5 Virtually impossible. Very easy.	0 1 2 3 4 5 We need to resolve this issue immediately. We can manage without near-term resolution.
Achieve design certification with one or more national regulators	0 1 2 3 4 5 Virtually impossible. Very easy.	0 1 2 3 4 5 We need to resolve this issue immediately. We can manage without near-term resolution.
Secure a first customer with intent to begin first-of-a-kind (FOAK) construction	0 1 2 3 4 5 Virtually impossible. Very easy.	0 1 2 3 4 5 We need to resolve this issue immediately. We can manage without near-term resolution.
Construct and commission the FOAK unit	0 1 2 3 4 5 Virtually impossible. Very easy.	0 1 2 3 4 5 We need to resolve this issue immediately. We can manage without near-term resolution.
Gain operational experience with the FOAK unit (fine-tuning operating parameters)	0 1 2 3 4 5 Virtually impossible. Very easy.	0 1 2 3 4 5 We need to resolve this issue immediately. We can manage without near-term resolution.
Secure additional customers (build an order book) to support a reactor module manufacturing facility	0 1 2 3 4 5 Virtually impossible. Very easy.	0 1 2 3 4 5 We need to resolve this issue immediately. We can manage without near-term resolution.
Construct and commission a manufacturing facility that will:		
Leverage advanced manufacturing techniques	0 1 2 3 4 5 Virtually impossible. Very easy.	0 1 2 3 4 5 We need to resolve this issue immediately. We can manage without near-term resolution.
Lower the cost of manufacturing through modular construction of most plant components	0 1 2 3 4 5 Virtually impossible. Very easy.	0 1 2 3 4 5 We need to resolve this issue immediately. We can manage without near-term resolution.
Expand the production line and leverage economies of volume	0 1 2 3 4 5 Virtually impossible. Very easy.	0 1 2 3 4 5 We need to resolve this issue immediately. We can manage without near-term resolution.

Session 1 – Page 3

Session 2: Discussion and assessment of technical barriers to SMR deployment

Session chair: Andreas Pautz, Paul Scherrer Institut

We will next hear a series of brief technical presentations by Dr. Shikha Prasad on six reactor designs, while workshop staff compile the results of the previous exercise for presentation later in the morning.

09:20 – 09:30	**Taxonomy of candidate designs**
09:30 – 09:40	**Babcock & Wilcox Generation mPower**
09:40 – 09:50	**Akademik Lomonosov KLT-40S Floating Nuclear Power Plant**
09:50 – 10:00	**Toshiba 4S reactor**
10:00 – 10:10	**High Temperature Reactor – Pebble-bed Module**
10:10 – 10:20	**SVBR-100 reactor**
10:20 – 10:30	**General Atomic's Energy Multiplier Module**

10:30 – 11:30 Building on the previous presentations, we will now spend 15 minutes each in two open discussions of two major challenges associated with SMR deployment. After each discussion, we will ask you to record your views. The challenges are:

Challenge 1. Reactor security: Characteristics of the fuel cycle and proliferation resistance

Challenge 2. Reactor safety: Inherent safety of reactor designs

Challenge 1. Reactor security:
Characteristics of the fuel cycle and proliferation resistance
Please compare the fuel characteristics of each of the six designs previously introduced. Focus on fuel composition, fuel loading, chemical composition, ease of spent fuel reprocessing, and other characteristics of the fuel cycle that have direct impact on reactor security.

For each of the 4 criteria below, which design poses the greatest challenge with respect to the listed criteria?

Criterion 1. Fresh fuel composition and enrichment levels	**Please use the space below to explain briefly the reasoning that underlies your choice:**
☐ B&W Generation mPower	
☐ KLT-40S floating NPP	
☐ Toshiba 4S fast reactor	
☐ High temp, pebble-bed	
☐ SVBR-100 fast reactor	
☐ GA EM^2 fast reactor	
☐ All roughly the same	
☐ Cannot determine	

Criterion 2. Spent fuel composition, handling, and storage	**Please use the space below to explain briefly the reasoning that underlies your choice:**
☐ B&W Generation mPower	
☐ KLT-40S floating NPP	
☐ Toshiba 4S fast reactor	
☐ High temp, pebble-bed	
☐ SVBR-100 fast reactor	
☐ GA EM^2 fast reactor	
☐ All roughly the same	
☐ Cannot determine	

Criterion 3. Core life-time and refueling plans	**Please use the space below to explain briefly the reasoning that underlies your choice:**
☐ B&W Generation mPower	
☐ KLT-40S floating NPP	
☐ Toshiba 4S fast reactor	
☐ High temp, pebble-bed	
☐ SVBR-100 fast reactor	
☐ GA EM^2 fast reactor	
☐ All roughly the same	
☐ Cannot determine	

Criterion 4. Transport of fresh and spent nuclear fuel	**Please use the space below to explain briefly the reasoning that underlies your choice:**
☐ B&W Generation mPower	
☐ KLT-40S floating NPP	
☐ Toshiba 4S fast reactor	
☐ High temp, pebble-bed	
☐ SVBR-100 fast reactor	
☐ GA EM^2 fast reactor	
☐ All roughly the same	
☐ Cannot determine	

Does one design pose a greater challenge to licensing than others?	**Please use the space below to explain briefly the reasoning that underlies your choice:**
☐ B&W Generation mPower	
☐ KLT-40S floating NPP	
☐ Toshiba 4S fast reactor	
☐ High temp, pebble-bed	
☐ SVBR-100 fast reactor	
☐ GA EM^2 fast reactor	
☐ All roughly the same	
☐ Cannot determine	

If you need more space, please feel free to write on the reverse side of this page.

Given what we know about fuel and waste, are any of the six designs *inherently more resistant* to proliferation than the others?

☐ Yes. ☐ No, all are probably about the same.

If you answered yes, please check the one design that you believe is:

Most resistant to proliferation	Least resistant to proliferation
☐ B&W Generation mPower	☐ B&W Generation mPower
☐ KLT-40S floating NPP	☐ KLT-40S floating NPP
☐ Toshiba 4S fast reactor	☐ Toshiba 4S fast reactor
☐ High temp, pebble-bed	☐ High temp, pebble-bed
☐ SVBR-100 fast reactor	☐ SVBR-100 fast reactor
☐ GA EM^2 fast reactor	☐ GA EM^2 fast reactor

A recent report of the U.S. National Research Council asserts that the assessment of proliferation resistance is *very* challenging, and that all available methods of evaluation have serious shortcomings.[1]

Some small modular reactor designs promise to reduce the risk of proliferation, or, at the very least, not measurably increase that risk. However, some worry that SMRs could increase some proliferation risks, or perhaps even create new security concerns.

On the next two pages, we ask you to assess factors that could lead to non-proliferation improvements, as well as factors that might result in greater concerns about proliferation.

[1] U.S. National Research Council, *Improving the Assessment of Proliferation Risk of Nuclear Fuel Cycles*, 2013.

First – what are your views about factors that might lead to **non-proliferation improvements**? As we discuss the candidates below, please check two boxes: the factor that you consider most important, and the one that you consider second-most important:

	Most important	2nd most important	
a.	☐	☐	Infrequent refueling
b.	☐	☐	Smaller core inventory
c.	☐	☐	Standardization could enable reduction of required safeguards checks
d.	☐	☐	Unattractive spent nuclear fuel composition for weapons proliferation
e.	☐	☐	Underground placement
f.	☐	☐	Automated and/or remote monitoring
g.	☐	☐	Sealed designs
h.	☐	☐	Other: ____

Second – what are your views about factors that might lead to **greater concerns about proliferation**? Some of these factors might not be applicable to all reactor designs. As we discuss the candidates below, please check two boxes: the factor that you consider most important, and the one that you consider second-most important:

	Most important	2nd most important	
a.	☐	☐	Increased deployment: increased monitoring and more resources needed
b.	☐	☐	Smaller fuel size could facilitate concealment and transportation
c.	☐	☐	Higher enrichment
d.	☐	☐	Difficult to solve hostage situations for underground reactors
e.	☐	☐	Low thermal footprint could make remote-sensing challenging for underground reactors
f.	☐	☐	Lack of core access for verification and monitoring in some designs
g.	☐	☐	Breeder technologies
h.	☐	☐	Vertical stacking of spent nuclear fuel
i.	☐	☐	Other: ____

One strategy that might limit proliferation risks could be the use of full "build-own-operate" packages.

What is the probability that, in 20 years, some SMR manufacturer will be offering developing countries a "full build-own-operate" package that includes all fuel handling and the removal of all spent fuel out of the country?

0	0.33	0.66	1
No chance it will happen.			Definitely it will happen.

If only some manufacturers offered such a package, what effect would that likely have on that company's comparative advantage in the market?

☐ Large positive ☐ Modest pos. ☐ No real effect ☐ Modest negative ☐ Large neg.

Please explain your reasoning:

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If a manufacturer sells reactors and offers training for local nationals to operate, perform refueling, etc. how would that affect the probability that SMRs in the developing world will lead to proliferation.

☐ Large increase ☐ Modest increase ☐ No real impact

Please explain your reasoning:

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If you need more space, feel free to write below or on the reverse side of this page.

Challenge 2. Reactor safety:
Inherent safety of reactor designs
How reliant are each of these designs on staff support, both for safety and security? Safety: do some designs eliminate certain initiating events? Are some so safe that they can be operated with fewer staff?

For each of the safety criteria listed below, which design poses the greatest challenge and which poses the least?

	Greatest challenge	Least challenge	Cannot determine
Adequate heat removal			☐
Reactivity control			☐
Material and structural integrity			☐
Containment of radioactivity			☐

Are any of the six designs more inherently safe than the others?

☐ Yes ☐ No, all are probably about the same

If you answered yes, please indicate the one design that you believe is:

Most inherently safe	Least inherently safe
☐ B&W Generation mPower	☐ B&W Generation mPower
☐ KLT-40S floating NPP	☐ KLT-40S floating NPP
☐ Toshiba 4S fast reactor	☐ Toshiba 4S fast reactor
☐ High temp, pebble-bed	☐ High temp, pebble-bed
☐ SVBR-100 fast reactor	☐ SVBR-100 fast reactor
☐ GA EM^2 fast reactor	☐ GA EM^2 fast reactor

Given the design you checked as most inherently safe, are there circumstances under which a major accidental release could occur, without operator intervention?

▢ Yes ▢ No

Is the design sufficiently inherently safe that the plant could be operated with fewer security staff?

▢ Yes ▢ No

It is conceivable that regulators would allow fewer security staff?

▢ Yes ▢ No

What do you see as the two or three most important issues with regard to making advanced SMRs inherently safe?

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11:30 – 11:45	Break for coffee, tea, juice
11:45 – 12:00	Presentation of the results from the morning card sorting and ranking exercises.
12:00 – 12:30	Discussion of results from the morning sessions. Opportunity for participants to change their card rankings and assessments.
12:30 – 13:30	Lunch

Session 3: Talks on a few key developments around the world

Session chair: Shikha Prasad, Carnegie Mellon University

13:30 - 15:00	Status report on IAEA's work on SMRs *M. HadidSubki, International Atomic Energy Agency (15 mins)*
	Status report on NRC's proposed approach to licensing SMRs *Ahmed Abdulla, Carnegie Mellon University (15mins)*
	Overview of U.S. Department of Energy's work on developing SMRs *Edward McGinnis, U.S. Department of Energy (15 mins)*
	Overview of Chinese work on developing and deploying SMRs *H. Keith Florig, University of Florida (30mins)*
	Overview of Russian work on developing and deploying SMRs *Nadeja Victor, U.S. National Energy Technology Laboratory (15mins)*
15:00 – 15:15	Break for coffee, tea, juice

Feel free to share any thoughts or comments you may have:

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Session 4: Exploring institutional and regulatory arrangements for SMR deployment in the developing world.

Session chair: Inês L. Azevedo, Carnegie Mellon University

15:15 – 16:00 In this session, we will spend about 20 minutes discussingeach of two topics. In each case, our focus will be on the issues that will arise if SMRs are deployed in the developing world. When it is useful to make the discussion less abstract, feel free to cite examples from among the following:

Africa	Asia	Middle East	Latin America
Ghana	Bangladesh	Egypt	Argentina
Kenya	Indonesia	Jordan	Brazil
Nigeria	Malaysia	Morocco	Chile
South Africa	Mongolia	UAE	Mexico
	Vietnam		

Topic 1. Regulation and certification: What standards is the world likely to use to regulate SMRs deployed in the near-term? If evolving national standards govern near-term deployment, will a similar patchwork framework of regulations govern deployment in 2050? If not, what developments might occur that could change that situation? Should we move towards a framework of international certification of smaller reactors? How likely is an international regulatory regime to emerge?

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Topic 2. Supporting infrastructure including emergency response: Deploying nuclear energy for electric power generation or for process heat is not just a matter of buying and installing a reactor. It also requires a range of supporting infrastructure for both routine and emergency situations. What alternative arrangements might be developed to address these issues? How difficult and expensive is it for a nation to develop such capabilities? Is it possible for a developing nation to outsource all of these issues as part of a "build-own-operate" package deal? Given that a reactor accident anywhere in the world has implications for the entire industry, is a greater international role warranted in emergency response?

Please feel free to use the reverse side of this page if you need more space.

Session 5: Identification of some key international issues

Session chair: Ahmed Abdulla, Carnegie Mellon University

16:00 – 17:40 In this final session of the first day, we will spend 20 minutes discussing each of the five topics below in order to lay the groundwork for discussion of a number of issues on day two of the workshop.

Topic 1. What unique issues are posed by the mass international deployment of factory-fabricated modules? What happens if a design flaw in a reactor causes an accident in Nigeria, when there are five such reactors in China? Can the industry handle the spate of retrofits that would be required to deal with such events? Are they liable?

Topic 2. How likely is it that decisions made politically will affect the extent of SMR penetration? Should the stability of a host nation be a criterion when choosing where to export these reactors? Would that violate the letter (never mind the spirit) of international law?

Topic 3. For nuclear power to gain greater acceptance, should we seek to *maintain* the existing nuclear governance regime as SMRs enter the market, or should we seek to change it (for the better)? *How* do we enhance it? For instance, should initiatives to institute a material control and accounting system for special nuclear material be instituted with greater urgency before SMR units are deployed in great numbers?

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Topic 4. What are the benefits for both exporter and host nation if we limit the amount of human capital required to build and run these reactors? Do the benefits for host nations outweigh the costs (prestige and development of human capital)? Are there nations that would welcome such reactors? How central a guiding principle should the limiting of knowledge transfer be when developing and deploying SMRs?

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Topic 5. In countries where export controls are more stringent than Nuclear Suppliers Group requirements (for instance, in the U.S.), how much of a distinct disadvantage does this pose to the vendors?

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Please feel free to use the reverse side of this page if you need more space.

17:40 – 17:45	Overview of plans for day 2
17:45	Adjourn for drinks and group dinner

Session 6: Three views of a future world of SMRs.

Session chair: M. Granger Morgan, Carnegie Mellon University

08:45 – 09:45 We will begin this session with a brief presentation of three alternative views of the international environment in which SMRs might be deployed over next several decades.

For the purposes of this exercise, we will assume that:

- no new major nuclear accidents occur that result in significant changes in public perceptions or concerns;
- some states with larger electricity systems continue to build large reactors; and,
- interest grows in the use of energy sources that do not emit carbon dioxide to the atmosphere for a range of applications (e.g. electric power, water desalination, process heat, production of hydrogen or ammonia, etc.)

09:45 – 10:15 General discussion, and possible refinements or elaborations for the three futures.

10:15 – 10:30 Break for coffee, tea, juice

10:30 – 11:00 The sheets on the pages that follow contain exercises that will elicit your thoughts regarding:

1) the future you feel we are most likely to achieve; and
2) the future that will, in your judgment, help nuclear power realize the greatest market penetration and share of power production.

Moreover, we will also ask you to compile a list of the advantages and disadvantages of these two futures

We will also give you an opportunity to describe your view of an alternative future if you have one.

Question 1. Most likely future: We presented and discussed three views of the international environment that might evolve in the next 20 years to govern the deployment of SMRs. In your judgment, which of these futures is **most likely**?

You have been given 20 chips. **Please divide them among the three futures to show the odds you would give that each will describe the state of affairs in 20 years.** After dividing the chips, **make sure you write down** the number of chips you have assigned to each future in the box provided.

A: Business as usual. All existing elements of the international nuclear governance regime remain in place:

- **Exports of nuclear technologies are limited to countries that are in compliance with their obligations under the Nuclear Nonproliferation Treaty (NPT) and have instituted full-scope IAEA safeguards, or, if outside the NPT, are in compliance with nonproliferation and nuclear security and safety guidelines suggested by the Nuclear Suppliers Group;**
- No new international agreements with legally binding obligations are made about the export, use, or operation of nuclear technologies;
- Management and operation of SMRs remain the responsibility of operators in host nations; this includes spent fuel stockpile management; and
- Aside from any international obligations stemming from compliance with the NPT, manufacturers of SMRs located in different nations face different levels of nationally imposed controls on export of nuclear tech. and know-how.

Place chips here. Write the number of chips in this box.

B: Mixed export limitations. There is a new international agreement among supplier states that:

- Places no restrictions on SMR export to nations that comply with the international nuclear governance regime outlined in **future A** above;
- Allows export of SMR systems of any design to any nation so long as the exporting manufacturer retains full management and operating responsibility across the entire fuel cycle and retrieves and returns all spent fuel to its country of origin, or to an internationally secure location (i.e. a full "build-own-operate" model); and
- Forbids export of any reactor that involves on-site refueling and fuel storage in the field (i.e. only pre-fueled, sealed reactor vessels allowed) to any host country or operator that does not have well-developed nuclear infrastructure and is not in clear compliance with the international nuclear governance regime discussed in **future A** above.

Place chips here. Write the number of chips in this box.

C: Strict export limitations. There is a new international agreement among supplier states, a primary stipulation of which is the formation of a globally representative consortium of manufacturers and fuel suppliers that:

- Harmonizes policy and practices for legacy contracts and stipulates that large LWRs can only be sold in countries that comply with the nuclear governance regime depicted in **future A**;
- Manages the manufacture at protected locations of sealed, pre-fueled SMR reactors for all export markets under a full "build-own-operate" and requires that all spent sealed SMR reactor modules be returned at the end of their service life to the internationally approved and supervised originating facility; and
- Establishes and operates a global accounting system for all fissionable isotopes.

Place chips here. Write the number of chips in this box.

What are the advantages and disadvantages of the future you feel is "most likely"?

Please note which future you deem most likely: Future ____________

Advantages	**Disadvantages**

Question 2. Most desirable future: Now, in your judgment, which of these futures is **most desirable** for the safe, expanded, and global deployment of nuclear power? Which would help nuclear power realize the greatest market penetration and share of power production in the next 20 years?

You have been given 20 chips. **Please divide them among the three futures to show the relative desirability of each future.** After dividing the chips, **make sure you write down** the number of chips you have assigned to each future in the box provided. When answering, please consider all relevant stakeholders: vendors, regulators, policymakers, customers, and of course the public at large.

A: Business as usual. All existing elements of the international nuclear governance regime remain in place: • **Exports of nuclear technologies are limited to countries that are in compliance with their obligations under the Nuclear Nonproliferation Treaty (NPT) and have instituted full-scope IAEA safeguards, or, if outside the NPT, are in compliance with nonproliferation and nuclear security and safety guidelines suggested by the Nuclear Suppliers Group;** • No new international agreements with legally binding obligations are made about the export, use, or operation of nuclear technologies; • Management and operation of SMRs remain the responsibility of operators in host nations; this includes spent fuel stockpile management; and • Aside from any international obligations stemming from compliance with the NPT, manufacturers of SMRs located in different nations face different levels of nationally imposed controls on export of nuclear tech. and know-how.	Place chips here. Write the number of chips in this box.
B: Mixed export limitations. There is a new international agreement among supplier states that: • Places no restrictions on SMR export to nations that comply with the international nuclear governance regime outlined in **future A** above; • Allows export of SMR systems of any design to any nation so long as the exporting manufacturer retains full management and operating responsibility across the entire fuel cycle and retrieves and returns all spent fuel to its country of origin, or to an internationally secure location (i.e. a full "build-own-operate" model); and • Forbids export of any reactor that involves on-site refueling and fuel storage in the field (i.e. only pre-fueled, sealed reactor vessels allowed) to any host country or operator that does not have well-developed nuclear infrastructure and is not in clear compliance with the international nuclear governance regime discussed in **future A** above.	Place chips here. Write the number of chips in this box.
C: Strict export limitations. There is a new international agreement among supplier states, a primary stipulation of which is the formation of a globally representative consortium of manufacturers and fuel suppliers that: • Harmonizes policy and practices for legacy contracts and stipulates that large LWRs can only be sold in countries that comply with the nuclear governance regime depicted in **future A**; • Manages the manufacture at protected locations of sealed, pre-fueled SMR reactors for all export markets under a full "build-own-operate" and requires that all spent sealed SMR reactor modules be returned at the end of their service life to the internationally approved and supervised originating facility; and • Establishes and operates a global accounting system for all fissionable isotopes.	Place chips here. Write the number of chips in this box.

What are the advantages and disadvantages of the future you feel is most desirable for the safe, expanded, and global deployment of nuclear power?

Please note which future you deem most desirable: Future ____________

Advantages	Disadvantages

Do you have an alternative vision for a world where SMRs can be deployed globally in a safe and secure manner?

If so, please briefly explain you vision below and note its advantages and disadvantages.

Description: ____

____

____

____

____

Advantages	Disadvantages

Session 7: What institutional barriers need to be overcome in order to achieve mass deployment of SMRs?

Session chair: Andreas Pautz, Paul Scherrer Institut

13:00 – 14:30	In this session, we will assume that: • Mass factory production of SMRs has become a reality. • Costs have come down to the point that they are at, or below, those of other base-load sources of electricity and process heat. • A technically adequate arrangement has been devised to deal with waste in a secure way (either in an internationally supervised repository, or repositories in one or more nations that the world deems to be responsible).

Regardless of what you think about the desirability of mass deployment of SMRs, we will focus on identifying and discussing the primary non-technical and non-economic barriers to mass deployment. In no particular order, these include the following four:

P: Concerns about proliferation of nuclear materials. For example:
- Threat of terrorists who compromise nuclear facilities.
- Threat of terrorists who seek nuclear materials from any end of the fuel cycle for a bomb.
- Threat of terrorists who divert small amounts of materials from any end of the fuel cycle to make a dirty bomb.
- Threat of NPT signatories who cheat on their obligations.
- Threat of NPT non-signatories who seek more nuclear materials for nuclear programs.
- Threat of malicious actor compromising the fresh and spent fuel supply chain/transportation network.
- Poor material control and accounting resulting from increased deployment.

T: Political and regulatory restrictions on trans-boundary flows in nuclear technology. For example:
- Two-tiered system of nuclear trade (e.g. OECD vs. non-OECD).
- Existing export control restrictions.
- Increased export control restrictions due to geopolitical developments.
- Geopolitical sensitivities surrounding certain nations.
- Political desire to restrict the flow of nuclear knowledge.

S: Public concerns about reactor safety and/or waste. For example:
- Existing public perception issues surrounding nuclear technologies.
- Potential safety-related "events" at one SMR facility, bolstering opposition to others elsewhere in the world.
- Potential safety-related "events" at one conventional reactor, bolstering opposition to others elsewhere in the world.
- Mistakes in transporting waste to the supervised repository.
- Concerns about the security of waste storage systems and facilities.
- Concerns about environmental releases from waste storage systems and facilities.
- Philosophical objection to the "Faustian bargain."

I: Inadequate institutional infrastructures. For example:
- Insufficient collaboration among national regulators during design certification, leading to different deployment rules for the same SMR unit depending on location.
- Incompetent/inexperienced national regulators in states aspiring to deploy SMRs.
- Insufficient emergency response capability in many parts of the world.
- Inability of IAEA to prepare for and deal with SMRs.
- Inability of WANO to prepare for and deal with SMRs.

You may think of other non-technical and non-economic factors that present a large barrier. If you do, please identify one below:

O: ____

____

Using the letters to designate each, please quickly rank the barriers by the order of the magnitude of the challenge that you believe they present:

_____ > _____ > _____ > _____ >_____

If you feel strongly about the factor you ranked 1st, please explain your reasoning:

____

____

____

____

____

Question to the floor: If you listed an additional barrier, what was it? (We will post and assign identifying letters to all new barriers.)

If you find one or more of those other barriers compelling, please feel free to re-rank:

_____ > _____ > _____ > _____ > _____ > _____ >_____

Question to the floor: Now a show of hands on rankings.

Who listed P as 1st 2nd 3rd
Who listed T as 1st 2nd 3rd
Who listed S as 1st 2nd 3rd
Who listed I as 1st 2nd 3rd
We will now do the same for the additional barriers that you identified.

We will spend the balance of the session in open discussion of the three barriers that the group collectively judges to present the greatest obstacle to the mass deployment of SMRs.

14:30 – 14:45 Break for coffee, tea, juice.

Session 8: What should we talk about that we have yet to discuss, or have not discussed sufficiently?

Session chair: Ahmed Abdulla, Carnegie Mellon University

14:45 – 15:15	Over the past two days, we have discussed both technical and institutional barriers standing in the way of SMR development and deployment. We'll now spend some time going around the room, asking each participant to identify issues that he or she thinks have notreceived sufficient attention over the course of the workshop. We'll classify these in real time and ask everyone to indicate which two they would like to discuss in the final hour.
15:15 – 16:30	Discussion of the two most neglected topics.
16:30	Thanks and adjourn to wine and cheese.

■

Feel free to share any comments or thoughts you may have
about the topics discussed over the past two days:

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Cards used for the ranking exercise in session 1

On-time, on-budget delivery of first few plants Rank the cards by importance (1 = most important)	Write down rank here
A build-own-operate paradigm Rank the cards by importance (1 = most important)	Write down rank here
Sealing reactor modules with fuel in the factory and eliminating on-site refueling Rank the cards by importance (1 = most important)	Write down rank here
Decreasing reactor size/inventory to reduce consequences of radioactive release Rank the cards by importance (1 = most important)	Write down rank here
Tagging of nuclear material or international material accounting system Rank the cards by importance (1 = most important)	Write down rank here

Internationalizing the fuel cycle: mining, milling, processing, fabrication, reprocessing/waste storage

Write down rank here

Rank the cards by importance (1 = most important)

Increasing global competition by bringing multiple SMR designs to market

Write down rank here

Rank the cards by importance (1 = most important)

An international design certification regime

Write down rank here

Rank the cards by importance (1 = most important)

An international regulatory framework

Write down rank here

Rank the cards by importance (1 = most important)

Inherent safety of design and improved operational safety

Write down rank here

Rank the cards by importance (1 = most important)

Automation of plant operation and fuel handling, allowing for fewer plant operators and personnel

Write down rank here

Rank the cards by importance (1 = most important)

Development of global crisis response and crisis management capabilities

Write down rank here

Rank the cards by importance (1 = most important)

SMRs that cost less per kW_e than conventional reactors

Write down rank here

Rank the cards by importance (1 = most important)

Scalability that allows for the ability to serve smaller markets and multi-module deployment

Write down rank here

Rank the cards by importance (1 = most important)

Establishing restrictions on the types of fuel used and binding limits on the levels of enrichment

Write down rank here

Rank the cards by importance (1 = most important)

Blank card

Write down
rank here

Rank the cards by importance (1 = most important)

Blank card

Write down
rank here

Rank the cards by importance (1 = most important)

Card used for the chip allocation exercise in session 6

Session 6: Three views of a future world of SMRs

Please transcribe the results of the two chip-allocation exercises (question 1 and question 2) into this sheet, which workshop organizers will collect.

Question 1: most likely future		***Question 2: most desirable future***	
A: Business as usual		**A:** Business as usual	
B: Mixed export limitations		**B:** Mixed export limitations	
C: Strict export limitations		**C:** Strict export limitations	
	Total = 20		**Total = 20**