Evaluating the Cost, Safety, and Proliferation Risks of Small Floating Nuclear Reactors

Michael J. Ford,1,* Ahmed Abdulla,2 and M. Granger Morgan1

It is hard to see how our energy system can be decarbonized if the world abandons nuclear power, but equally hard to introduce the technology in nonnuclear energy states. This is especially true in countries with limited technical, institutional, and regulatory capabilities, where safety and proliferation concerns are acute. Given the need to achieve serious emissions mitigation by mid-century, and the multidecadal effort required to develop robust nuclear governance institutions, we must look to other models that might facilitate nuclear plant deployment while mitigating the technology’s risks. One such deployment paradigm is the build-operate-return model. Because returning small land-based reactors containing spent fuel is infeasible, we evaluate the cost, safety, and proliferation risks of a system in which small modular reactors are manufactured in a factory, and then deployed to a customer nation on a floating platform. This floating small modular reactor would be owned and operated by a single entity and returned unopened to the developed state for refueling. We developed a decision model that allows for a comparison of floating and land-based alternatives considering key International Atomic Energy Agency plant-siting criteria. Abandoning onsite refueling is beneficial, and floating reactors built in a central facility can potentially reduce the risk of cost overruns and the consequences of accidents. However, if the floating platform must be built to military-grade specifications, then the cost would be much higher than a land-based system. The analysis tool presented is flexible, and can assist planners in determining the scope of risks and uncertainty associated with different deployment options.

KEY WORDS: Floating nuclear plant; nuclear economics; nuclear proliferation; nuclear safety; small modular reactor

1. INTRODUCTION

The prospects for increased deployment of nuclear power plants (NPPs) do not look good in Organization for Economic Development and Cooperation (OECD) economies.1 In the near-to-medium term, expansion in nuclear power generation is expected only in a few large or wealthy developing economies where electricity demand is growing rapidly.2 And yet, today, the technology is responsible for more than a tenth of the world’s total electricity supply, and remains one of only two proven, low-carbon sources of base-load power that can replace fossil fuels.3 It is difficult to see how we can decarbonize the world’s energy supply while simultaneously phasing out nuclear power. Indeed, many decarbonization studies assume the existence of a portfolio of reliable low-carbon options that include nuclear power, carbon capture and sequestration, and biomass plants.3,4 Of these, only nuclear has previously been deployed at scale.

Nuclear power has its risks, however, and radically expanding its use in emerging nuclear energy
states poses challenges for the institutions responsible for governing the technology. Developing nations contemplating their first nuclear plants face a multidecadal undertaking, one that involves capacity building and intense internal and external scrutiny. If the world is to avoid the most catastrophic impacts of global warming, the bulk of our mitigation efforts must take place in the next several decades.\(^6\) If its present design, licensing, construction, and deployment paradigms remain unchanged, it will be difficult or impossible for nuclear power to play more than a small role in the move toward a decarbonized energy system. Existing light water reactor designs, even Generation III+ variants, carry with them a high potential for cost overrun due to long development times, high long-lived radioactive waste generation, and limited potential for the gains in plant efficiency that could lead to better economic competitiveness. Some advanced designs, such as molten salt or high-temperature gas cooled reactors, could mitigate many of these shortcomings, but design and development of these alternatives, while it has recently generated significant interest, has not led to a clear path for near-term deployment. Given the short timeframe required for successful mitigation, advanced nuclear designs are unlikely to be deployed at scale before mid-century.

One of the few remaining alternatives to retaining nuclear as part of the solution is a radical change in the deployment paradigm for reactors based on light water designs that may mitigate some of the historical shortfalls. This article explores such a change, which involves an advanced supplier nation building, owning, and operating a fleet of small modular nuclear reactors (SMRs). These SMRs would be sited on offshore platforms, and their power transmitted to host nations via undersea power cables. Once their fuel is spent, they would be returned to a centralized facility for refueling and waste processing. These floating small modular reactors (fSMRs) might mitigate some of the risks associated with land-based reactors, enhancing safety and economic viability, while the build-own-operate-return (BOOR) model should help to reduce the material proliferation risks.

2. A NEW MODEL OF NUCLEAR POWER PLANT DEPLOYMENT

SMRs—which have a power output of less than 300 megawatts-electric MW\(_e\)\(^7\)—have been touted for the past decade as an option for communities in remote locations\(^8\) for developing nations keen on meeting their growing energy demands using low-carbon sources\(^9\) and even for replacing aging coal-fired energy infrastructure in the United States\(^10\). Work to date has focused on the potential advantages of using modular construction processes in the assembly of major plant components. It is argued that factory-based manufacturing will allow for better cost and quality control, ultimately lowering the risk of cost overrun, something that has plagued NPP development in the past.\(^11\) Some analysts even raise the possibility of cost reduction through technological learning, should the volume of plant orders be sufficient.\(^10\)

The offshore deployment of NPPs is not a new concept.\(^12\) In the United States, one company worked through the 1970s to gain approval for the construction of eight floating gigawatt-scale NPPs,\(^4\) the first few of which were to be located off the coast of New Jersey.\(^13\) More recent proposals by the DCNS Group in France (a French military industrial conglomerate; DCNS stands for Direction des Constructions Navales Service),\(^14\) the Korea Advanced Institute of Science and Engineering,\(^15\) and the Massachusetts Institute of Technology\(^16\) have advocated the development of floating nuclear plants of various designs, mainly to circumvent siting restrictions on land, as well as negative public attitudes to nuclear power.

Even if nations can afford to opt for an SMR as a carbon-free base-load alternative, there are formidable regulatory and institutional hurdles that must be addressed, both immediately and in the long term.\(^17\) Relying on nuclear power demands virtually perpetual safety, security, and waste management commitments on the part of host nations.\(^18\) The indigenous development of these institutions requires a multidecadal undertaking, and importing the necessary human capital is impossible for all but the richest states (the United Arab Emirates began its program less than 10 years ago, and expects to commission its first reactor—which is on time and on budget—in 2017).\(^19\) Compounding the problem is the fact that proposed deployment strategies design out innovations that might address the safety, security, and waste implications of nuclear power, on the assumption that regulators will not approve significant deviations from current practice. This strategy is misguided, since novel deployment

\(^4\) The company, Offshore Power Systems, was a joint venture between Newport News Shipbuilding and Westinghouse.
paradigms can reduce the economic, safety, and security risks associated with NPP deployment.

One such paradigm, appropriate especially for emerging nuclear energy states that cannot afford the significant effort required to develop robust institutional oversight, is the BOOR model, which sees fueled modules deployed to customer nations, where they remain in operation until end of core life, at which point they are safely returned to centralized, supervised facilities for refueling and waste handling. However, reactor designers from the United States, China, India, Korea, and Russia with whom we have conferred argue that, for the foreseeable future, shipping a fully fueled light water reactor to and from a land-based location presents technical and safety issues that are likely to make costs prohibitive for a developing nation.

We have constructed an assessment model in the Analytica (Lumina Decision Systems, Los Gatos, CA 95033, USA) software package to compare the economic, safety, and security risks of a land-based SMR with an iSMR that closely adheres to the BOOR model. We took the International Atomic Energy Agency’s (IAEA) Siting Criteria as our starting point. These, along with the IAEA’s specific safety guides, are used in determining the suitability of new sites for NPP deployment. The complete list of criteria is shown in Table A1 in Appendix A. We focused on criteria associated with the NPP parameter envelope, as well as the engineering and cost factors, which restricted our analysis to criteria that are different by nature of the two deployment options.

3. EVALUATING OFFSHORE PLANTS THAT ADHERE TO THE BOOR MODEL

Building an iSMR plant that adheres to the BOOR model has several advantages related to material control, proliferation risk, and operational risk. (1) The entire deployment process can be modularized: historically, land-based NPP construction—much unlike shipbuilding—was so site-specific that little to no technological learning occurred over multiple installations. Standardization of land site development has always been the goal. The French nuclear program has come closest to achieving this but with only limited success. With a floating model, construction of plant components and many site-specific considerations could be standardized, exploiting learning economies and limiting the risk of cost overruns in the process. Depending on water depth, timelines for development could potentially be shorter, and should cause less disruption, since they would not entail the assembly of myriad complex plant components in a specific order and onsite. As noted by the IAEA, the predominant risk factor affecting the construction timeline of new land-based plants is civil and structural work, such as excavation, tsunami protection, seismic stabilization, and foundation development.

(2) Internationalizing the nuclear fuel cycle: over the years, there have been many calls for improved international management and supervision of the nuclear fuel cycle, mainly in order to limit proliferation risk. The reactor system we evaluate here, which adheres to the BOOR model, transforms nations interested in nuclear power into contracting nations. The responsibilities associated with refueling and waste handling are managed completely outside the purview, eliminating cost and risk drivers that might overwhelm inadequate institutions, and reducing the risk of material diversion. Nuclear fuel and waste would be managed in a nuclear-capable state under stringent material control and accounting practices, reducing the risk of proliferation and focusing IAEA resources into monitoring fewer sites.

(3) Increased energy delivery: with this model, the vendor can deliver power at a high (90%) capacity factor (CF) and, if a substitute barge is provided as a replacement for one that is at the end of its core life, the CF would exceed that of typical gigawatt-scale reactors, eliminating the need for alternative generating capacity in the process. The increase in CF results from elimination of downtime during refueling, which is typically 4–5% of the ~10% total downtime for nuclear plants. Increased CF can be seen in the history of existing plants as refueling periods have shrunk, leading to increasing overall CF for U.S. plants.

(4) Seismic and tsunami risk mitigation: if sited in waters of sufficient depth (≥100 m), the risk to this platform from seismic or tsunami damage would be minimized, and the plant would not face difficulties in dealing with sea-level rise.

(5) Accident consequence mitigation: siting plants offshore limits the consequences of potential radionuclide releases, as detailed in Section 5.

(6) More limited span of control: plant

security is enhanced by the challenging nature of a waterborne approach and the narrower defense perimeter. Moreover, existing anti-swimmer systems, coupled with robust sensing systems under development, can yield a well-protected platform.

Offshore siting also has disadvantages. We discuss the cost of transmission and the different security risk profile in Section 5, but other disadvantages exist. (1) Extreme weather impacts: operating in a marine environment during extreme weather events can be challenging. However, unlike proposals for siting large reactors offshore, our fSMR BOOR design does not involve refueling on location; hence, there is no need for onsite heavy lift capability. In our design, operations that require significant maintenance—not to mention refueling—will be conducted in a secure dry dock. (2) Long-term maintenance: platform and component corrosion will become a life-cycle maintenance concern, and must be addressed in any offshore platform proposal. Cathodic protection systems, which are systems designed to prevent corrosion of metal components in hull and seawater systems, would be necessary (typical in most marine platforms), and periodic docking will be required for any barge-based plant like ours. (3) Logistics and staffing: a model akin to that used by deep-water oil platforms will be required to manage daily operations and staff the plant. Shore node to ocean terminal logistics infrastructure will need to be established at each new site, and the unique environment will entail a potentially higher salary structure than that followed by land-based sites. (4) Risk of ocean releases: a clear concern in the event of an accident is the contamination of the ocean environment. The smaller core load and lower core damage frequency expected for SMRs reduce the risk when compared to large reactors, and the possibility that the barge could be towed to deep water if an accident begins could also mitigate contamination risks. Beyond the potential for radionuclide contamination of a coastal biota habitat, an accident could complicate return of the damaged reactor to vendor nations. (5) Licensing and regulation: this is potentially one of the most challenging issues. An offshore mobile platform, if positioned farther than 12 nautical miles (nm) from land, will pose international legal and regulatory challenges. Aside from the jurisdictional questions associated with regulatory oversight, deployment may necessitate more complex liability regimes to deal with transportation, emergency response in international waters, and long-term security and proliferation resistance in both host and vendor nations. Some similar issues have been partly addressed by icebreakers and naval ships that are powered by nuclear reactors.

Regarding the BOOR model itself, there are clearly regulatory, liability, and contracting issues associated with this model that may impact the specific application, cost, and viability for each host/vendor combination. Some wealthy but heretofore non-nuclear states may opt for a model that includes an ownership stake in the plant but relies on an external vendor to build, operate, and then take custody of the plant at end of life. Some elements of such agreements have already been successfully negotiated between host/vendor partners: the Emirates Nuclear Energy Corporation signed an Engineering, Procurement, Construction, and Operation Contract with its vendor, for example. Additionally, international development agencies could conceivably support the construction and operation of an fSMR in an emerging nation as a way to spur economic growth. It is not the intent of this article to explore those more detailed issues related to the business model, but clearly these will need treatment for any worldwide implementation.

4. METHOD

We used our Analytica model to investigate the relative cost of onshore and offshore siting, and to assess three key risks that would impact a decision to pursue either land-based or floating options. First, we analyzed how the two compare in terms of overnight cost and risk of cost growth, and the relative costs and risks of decommissioning, material, and transmission. Second, we explored whether an fSMR mitigates risk in the emergency planning zone (EPZ), and also considered the potential impacts of a marine accident. Third, we calculated the potential “water opportunity benefit” associated with a floating deployment method for host nations that have a limited water resource and face a high and growing demand for needs such as drinking water or irrigation. We used cost data gathered from a variety of literature sources on shipbuilding, nuclear development and decommissioning, transmission cost, material cost, and water withdrawal. Finally, we examined the proliferation advantages and disadvantages of an fSMR that adheres to the BOOR model. The proliferation question, due to its more speculative nature, was assessed qualitatively.

A few assumptions must be noted. Though there are multiple potential designs, the floating plant
model we describe here consists of a sea-based staging and electrical distribution platform (Fig. 1), with the reactor plants housed within articulated, ballastable barges that would be rigidly moored to the staging platform. First, this design is faithful to the BOOR model, and potentially simplifies construction, refueling, and maintenance. Second, it permits the use of ship and oil platform construction costs as analogs for floating SMR development. Third, the barge design is flexible enough to be used in other siting applications (e.g., pier-side operations in the arctic), expanding the set of potential customers. As for the land-based SMR, for this initial analysis, we assumed the site under investigation would contain one integral light water reactor, making it essentially a small light water reactor site. If an SMR could be designed that could be safely transported fully fueled to and from its use location, then a land-based BOOR deployment paradigm would be feasible. However, as noted above, most reactor design experts with whom we have conferred indicated that the shipment of either a fully fueled or spent light water reactor module to/from a developing world site would be a mammoth technical, economic, and institutional undertaking and with present designs is probably not feasible. As a result, a BOOR land site model was not included as a viable alternative to the floating option. Should advanced non light water reactors be developed, this option may well become possible in the future. As noted earlier, contracting vendors to operate the plants they build is possible, as experience in the Emirates shows. Regardless of land deployment paradigm (and as we will discuss in later sections), if a reactor is sited on the land of a sovereign state, it would be more easily accessed by state or other actors. If it is refueled on site, the same would be true of any spent fuel.

We draw our land-based SMR construction cost data from the literature that incorporates some of the cost benefits potentially inherent in land-based SMR deployment. Should grid capacity require more than a single SMR, scaling of both siting options to incorporate multiple reactors is certainly feasible but is not explored here. Reactor and turbine components are assumed to be the same for both options. Therefore, the comparison of construction costs for land and floating sites focuses on differences in engineering, procurement, and construction, as well as transmission yard, cooling system, and installation costs. All other equipment costs and owner’s costs are excluded from the comparison on the grounds that they would be identical. This includes refueling costs, which would be done every 24–30 months on location for a land-based site but would be done in a shipyard for the fSMR. Cooling water costs are only considered for the land site, since the floating platform is designed for cooling with ocean water. Our model allows us to estimate the water opportunity “benefit” that accrues when an fSMR option is compared to a competing land site that would use freshwater cooling due, for example, to limited coastal property availability, concerns with urban encroachment, or risks from climate change and extreme events. A 2010 study examining the risk to coastal energy
infrastructure in California indicated that there were potentially 30 power plants in the state—with a total generating capacity of over 10 K MW,—at risk of damage from a 100-year flood if a 1.4 M increase in sea levels occurs due to climate change. More recently, a 2014 study in Europe by Brown et al. indicates that as many as 71 NPPs—37% of the European coastal total—may be at risk of flooding and damage related to sea-level rise and extreme events. Of course, some nations may still choose to develop a land-based SMR on a coastal site, in which case this benefit would not be applicable. Note that while there would technically be no additional “cost” for cooling a land-based plant from freshwater sources, other than development of the appropriate piping and pumping systems, there is an opportunity cost for urban communities due to the land site’s significant water withdrawals, not to mention other concerns, including thermal pollution of smaller waterways.

As shown in Fig. 2, and as detailed further in Appendix B, our Analytica model consists of three major modules, one dedicated to the floating plant’s parameters, another to the land-based plant’s parameters, and a third that handles input/output. Each of the first two modules contains submodules dedicated to the costs under investigation: construction, EPZ, decommissioning, transmission, and materials. Additionally, the land-based plant has a submodule dedicated to the opportunity cost of using freshwater for cooling, while the floating module contains an assessment of the impacts of a marine accident. Using the input/output page, an analyst can choose parameter values for each of the model’s variables. In the results reported here, probability distributions are used to allow influence assessment of key parameters, though the modelers can change the type of parameter or distribution to suit requirements. As it stands, the model provides a differential comparison of the two siting methods, which is presented as a “floating value minus land value.” We adopted this approach in order to develop cumulative distribution functions (CDFs) that allowed assessment of the probability of differential (as opposed to absolute) costs based on variable assumptions. Table I provides a summary of key nodes, values, and sources for the floating reactor plant, and Table II does the same for the land-based plant. Throughout, costs are reported in $US \times 10^6$ (2012). For simulations involving chance nodes, 10,000 iterations were conducted. Appendix B contains a full description of the model, including a complete breakdown of model nodes and key calculations.

## 5. RESULTS AND DISCUSSION

### 5.1. Project Cost and Risk of Cost Growth

Our results indicate that deploying an fSMR that adheres to the BOOR vision has a number of advantages when compared to a land-based equivalent. The first question we asked in Section 4 was whether the floating option could achieve better control of cost than the land-based option. Using the values assumed in Tables I and II, there is a greater than 80% probability that the cost of the floating option will be lower than the land-based reactor’s if commercial shipbuilding costs apply. A 50,000–70,000 deadweight-ton double-hull barge, with a staging platform, a uniformly distributed 0–10% learning rate, and a security barrier would have a median cost of \$620 M (10th and 90th percentiles of \$400 M and \$770 M, respectively). Assuming no cost overrun, the land-based site, with a median specific cost of approximately \$5,300/kW\textsubscript{e}, would have a median cost of \$760 M (10th and 90th percentiles of \$660 M and \$850 M, respectively). As mentioned in the previous section, these costs are for the site and platform development only, and in both cases do not include reactor or turbine plant equipment, which we conservatively assume to be comparable across the two deployment options when considering “Nth of a Kind” development. In fact, costs of shipment/placement for plant components to host nations would most certainly lead to higher cost when compared with the development of fSMRs in a centralized facility. Figs. 3(a) and 3(b) show the CDFs for the two options and for the difference between them. An importance analysis indicates that the cost of the staging platform is the dominant cost factor in the floating plant.

At the other extreme, if military shipbuilding costs are assumed, the picture changes dramatically (Fig. 4). Our cost estimates consider vessels in the U.S. Navy’s surface fleet, with nuclear aircraft carriers, nuclear cruisers, and amphibious ships representing the bounds of our analysis. These vessels are built with material, reinforcement, weld inspections, etc., that all meet military specification (MILSPEC) specifications for combat vessels. When these costs are applied, the land-based reactor dominates the floating option. Fig. 5 shows that assumptions about hull form size and cost have the most influence on plant cost.

Ship construction is robust worldwide, and a prior U.S. assessment suggested that military hulls could be built overseas for one-third of their U.S.
### Table I. An Overview of the Main Variables in our Analytica Model’s Floating Module

<table>
<thead>
<tr>
<th>Module/Submodule</th>
<th>Range</th>
<th>Units</th>
<th>Distribution</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Floating</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Construction     | Hull form size—commercial | 50,000–70,000 | DWT | Uniform | Estimated mass of plant and ballast (deadweight).  
|                  | Hull form size—military (USN and ROW) | 10,000–25,000 | T | Uniform | USN Nuclear Guided Missile Cruiser;  
|                  | Hull prices—commercial | 300–750 | $/DWT | Triangular | UN Review of Maritime Transport;  
|                  | Hull prices—military | 30,000–75,000 | $/T | Truncated normal | CRS; USN Budget Justification documents;  
|                  | Hull—overrun | 0–30 | % | Uniform | Assumed overrun to account for unique nature of the hull form.  
|                  | Staging and distribution (S&D platform) prices | 300–750 | $ M | Uniform | Spar rrig costs expanded to account for unique structural configurations and more robust construction standards.  
|                  | S&D platform—overrun | 0–15 | % | Uniform | Assumed overrun to account for unique nature of the platform.  
|                  | Learning curve | 0.9–1 | – | Uniform | USN Virginia Class: fixed-price, multiunit contracting.  
|                  | Security barrier unit cost | $5 \times 10^{-4} – 7 \times 10^{-3}$ | $ M/m$ | Selectable | Estimate provided by Harbor Offshore Barriers.  
|                  | Security barrier radius | 200–1,000 | m | Selectable | Max range 1,000 m used as a bounding value.  
| **Trans.**       | Range | 1–10 | mi | Uniform | Max range 10 mi for consistency with EPZ value; Min range 1 mi.  
|                  | Cost per mile | 1–10 | $ M/mi | Truncated normal | Neptune Systems costs; Siemens; NorNed link costs; assumption of minimum cost of $1 M/mi.  
| **Decomm.**      | Decomm. cost | 85 | $ M | – | Code of Federal Regulations (value based on plant size).  
|                  | Energy cost index | 2.704 | – | Fixed | 2012 cost index.  
|                  | Labor cost factor | 1.5–3 | – | Selectable | NRC NUREG-1307.  
|                  | Burial cost factor | 6–32 | – | Selectable | NRC NUREG-1307.  
|                  | Plant size | 10,000–300,000 | kW$_e$ | Selectable | 225,000 kW$_e$ used as representative size for an SMR.  
|                  | Mil. decom. cost factor | 0.0004–0.001 | $ M/kW_e$ | Fixed |  
| **Mat.**         | Staging rig weight | 20,000–30,000 | T | Uniform | Kaiser.  
|                  | Hull form size | 10,000–20,000 | T | Uniform | USN Nuclear Guided Missile Cruiser.  
|                  | Cost of steel | 250–800 | $/T | Uniform | Steel on the Net; MEPS; and Steel Benchmark.  
| **EPZ**          | Distance from coast | 1–10 | mi | Uniform | Max range 10 mi for consistency with EPZ value; Min range 1 mi.  
|                  | Economic impact factor | 13–400 | $/pop/km^2$ | Triangular | Sovacool; TEPCO; Vasquez; IAEA.  
|                  | EPZ pathway distance | 10 or 50 | mi | Selectable | NRC EPZ planning ranges.  

**Units:** DWT, deadweight ton; T, ton; m, meter; mi, mile; kW$_e$, kilowatt-electric; pop, population; km, kilometer.  
USN, U.S. Navy; NPP, nuclear power plant; ROW, rest of world; CRS, Congressional Research Service; EPZ, emergency planning zone; NRC, U.S. Nuclear Regulatory Commission; TEPCO, Tokyo Electric Power Company; IAEA, International Atomic Energy Agency.  
Consult Appendix B for model description.
Fig. 2. An overview of the main page of our Analytica model, which has three major modules: one investigates the land-based SMR, another investigates the floating SMR, and a third allows the modeler to modify assumptions and data to evaluate a specific scenario. Appendix B contains a full description of the model.

In this case, the floating option’s cost would be approximately equivalent to the land-based option, again assuming that the latter experiences no cost overrun. To model this in an alternative fashion, we examined international shipbuilding cost metrics, which are based on compensated gross tonnage (CGT), a measure of the gross tonnage of a vessel corrected to account for platform type, size, and complexity. CGT calculations are spelled out by the OECD. While CGT calculations do not cover military platforms, a 2005 assessment of global shipbuilding considered the CGT methodology for more complex naval platforms and noted that international shipbuilding productivity (measured in man-hours/CGT) is almost twice that of U.S. naval shipyards. Additionally, labor costs in nations that conduct a predominant amount of commercial shipbuilding (e.g., South Korea and China) are lower. These factors strongly indicate that the hull form could be built for far less when using non-U.S. shipbuilding factors. Using factors from the global shipbuilding study, we modeled potential barge costs considering CGT and a “Customer Factor,” which varies from 1.06 to 1.18, to reflect the increased performance requirement that apply to a naval platform (and perhaps would apply to a floating NPP). When modeled using these factors, a CGT value of 25–30 would lead to costs that are equivalent to the mean land site cost of construction (nominally $750 M). Note that a very simple commercial hull form has a CGT factor as low as 0.3, while the most complex naval platform, a nuclear submarine, can be as high as 80. To highlight the impact of variation in world ship construction, the preeminent shipbuilding nation worldwide is South Korea, which recently announced the development of three new Aegis Destroyers at a unit cost of ~$934 M. The comparably sized military platform in the United States is an Arleigh Burke Class Destroyer, which is expected to cost ~$1.8 B per platform, or almost twice that of the South Korean platform.

Despite the very strong potential that the hull can be built for a reasonable cost on the international market, there is still a substantial construction cost risk with floating development. The cost benefit accrued to the floating option would quickly dissipate if delays or changing construction requirements lead to extended construction timelines. Even granting the much lower cost of building somewhere like South Korea, the greater requirements of building to military specifications still imply a cost in excess of $50,000 per ton (vs. $500–1,000/ton for conventional
### Table II. An Overview of the Main Variables in our Analytica Model’s Land-Based Module

<table>
<thead>
<tr>
<th>Module/Submodule</th>
<th>Range</th>
<th>Units</th>
<th>Distribution</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Land</strong>&lt;sup&gt;59&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Const. (Overnight costs)</td>
<td>3,000–7,200</td>
<td>$/kWe</td>
<td>Truncated normal</td>
<td>Abdulla et al.;&lt;sup&gt;60&lt;/sup&gt; Rothwell;&lt;sup&gt;61&lt;/sup&gt; U.S. EIA;&lt;sup&gt;62&lt;/sup&gt; Black and Yeatch.&lt;sup&gt;63&lt;/sup&gt;</td>
</tr>
<tr>
<td>Trans. (Site constr. cost factor)</td>
<td>0.635</td>
<td>–</td>
<td>Fixed</td>
<td>Max range 10 mi for consistency with EPZ value.</td>
</tr>
<tr>
<td>Range</td>
<td>0–10 mi</td>
<td>mi</td>
<td>Uniform</td>
<td>Greenwell;&lt;sup&gt;64&lt;/sup&gt; Edison Electric Institute;&lt;sup&gt;65&lt;/sup&gt; PG&amp;E;&lt;sup&gt;66&lt;/sup&gt; Wisconsin PU;&lt;sup&gt;67&lt;/sup&gt; National Council on Electricity Policy; assumption of minimum cost of $1 M/mi.</td>
</tr>
<tr>
<td>Cost per mile</td>
<td>0.1–2 $ M/mi</td>
<td></td>
<td>Truncated normal</td>
<td></td>
</tr>
<tr>
<td><strong>Decomm.</strong>&lt;sup&gt;68&lt;/sup&gt;</td>
<td>85</td>
<td>$ M</td>
<td>–</td>
<td>Code of Federal Regulations&lt;sup&gt;46&lt;/sup&gt; (value based on plant size).</td>
</tr>
<tr>
<td>Decommissioning cost</td>
<td>2.704</td>
<td>–</td>
<td>Fixed</td>
<td>NRC NUREG-1307;&lt;sup&gt;46&lt;/sup&gt; NRC NUREG-1307;&lt;sup&gt;46&lt;/sup&gt; CA DOT cost estimates;&lt;sup&gt;72&lt;/sup&gt;</td>
</tr>
<tr>
<td>Energy cost index</td>
<td>1.5–3</td>
<td>–</td>
<td>Selectable</td>
<td>UC Berkeley;&lt;sup&gt;69&lt;/sup&gt; ORNL.&lt;sup&gt;70&lt;/sup&gt;</td>
</tr>
<tr>
<td>Labor cost factor</td>
<td>6–32</td>
<td>–</td>
<td>Selectable</td>
<td>ENR Construction;&lt;sup&gt;71&lt;/sup&gt; IAEA.</td>
</tr>
<tr>
<td>Burial cost factor</td>
<td>100–160 $/m³</td>
<td>Uniform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plant size</td>
<td>10,000–300,000 kW&lt;sub&gt;e&lt;/sub&gt;</td>
<td>Selectable</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mat.</strong>&lt;sup&gt;10&lt;/sup&gt;</td>
<td>250–800 $/T</td>
<td>Uniform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of steel</td>
<td>See model</td>
<td>Selectable</td>
<td></td>
<td>UC Berkeley;&lt;sup&gt;68&lt;/sup&gt; ORNL.&lt;sup&gt;70&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>EPZ</strong>&lt;sup&gt;53&lt;/sup&gt;</td>
<td>1–10</td>
<td>mi</td>
<td>Uniform</td>
<td>Max range 10 mi for consistency with EPZ value; Min range 1 mi.</td>
</tr>
<tr>
<td>Distance from coast</td>
<td>10–200 pop/km²</td>
<td>Uniform</td>
<td></td>
<td>NRC Guidance Manual 4.7;&lt;sup&gt;53&lt;/sup&gt;</td>
</tr>
<tr>
<td>Economic impact factor</td>
<td>13–400 $/pop/km²</td>
<td>Triangular</td>
<td></td>
<td>Sovacool;&lt;sup&gt;54&lt;/sup&gt; TEPCO;&lt;sup&gt;55&lt;/sup&gt; Vasquez;&lt;sup&gt;56&lt;/sup&gt; IAEA.&lt;sup&gt;57&lt;/sup&gt;</td>
</tr>
<tr>
<td><strong>Water</strong>&lt;sup&gt;73&lt;/sup&gt;</td>
<td>1–30 HCF</td>
<td>Triangular</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water volume</td>
<td>10 or 50 mi</td>
<td></td>
<td>Selectable</td>
<td>NREL;&lt;sup&gt;73&lt;/sup&gt; NETL;&lt;sup&gt;74&lt;/sup&gt; MIT;&lt;sup&gt;75&lt;/sup&gt; NEI;&lt;sup&gt;76&lt;/sup&gt; WNA;&lt;sup&gt;77&lt;/sup&gt;</td>
</tr>
<tr>
<td>Water cost</td>
<td>3–10 $/HCF</td>
<td></td>
<td>Triangular</td>
<td>San Diego Water District;&lt;sup&gt;78&lt;/sup&gt; Seattle;&lt;sup&gt;79&lt;/sup&gt; comparative overseas rates;&lt;sup&gt;80&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

**Units:** kWe, kilowatt-electric; mi, mile; T, ton; m, meter; pop, population; km, kilometer; HCF, hundred cubic feet.


Consult Appendix B for model description.

---

5.2. Decommissioning, Transmission, and Material Costs

There are significant differences between the two options when it comes to decommissioning, transmission, and material costs as well. The (sparse) evidence that exists suggests that the same benefits that accrue to floating reactors during the construction phase (mainly the centralized construction location) accrue to them during the decommissioning phase. In the United States and elsewhere, decommissioning costs are controlled by regulation. While it is unlikely that an fSMR operation would be based on commercial ship construction) when evaluating the cost of the Aegis destroyer example above. Ultimately, regulatory decisions have caused significant delay in past NPP developments, so well-run shipyards and designs developed to the minutest details will be a key to maintaining cost control.<sup>87</sup>

Our model indicates that barge costs likely need to remain below $16,000/ton (using a light displacement of 15,000 tons) to remain competitive with land-based deployment. Using CGT methodology, the CGT factor would likely need to remain below 30. Staging and distribution platform costs are assumed to mirror commercial spar-type oil platform costs.
Fig. 3. Cumulative distribution functions (a) comparing the construction costs of the floating and land-based SMR deployment options using cost data that comply with commercial shipbuilding specifications, and (b) showing the difference between the two options. Under this scenario, there is a >0.8 probability that the floating option will be cheaper than the land-based option.

Fig. 4. Cumulative distribution functions (a) comparing the construction costs of the floating and land-based SMR deployment options using cost data that comply with military shipbuilding specifications, and (b) showing the difference between the two options. Under this scenario, the construction cost of the land option consistently dominates that of the floating option.

Fig. 5. As our importance analysis shows, the size and price of the hull form are the factors of greatest consequence in our model when military construction specifications are assumed.

in the United States, for this model, baseline costs were assumed to follow U.S. NRC NUREG–1307 and 10 CFR 50.75 decommissioning funding guidelines, which are based on plant size. Because we assume equivalent plants, the net cost difference is zero. Required funding levels in the United States for an SMR site of 225 MWₑ vary depending on region, and can range from $300 to 700 M. Remediation of the site of a floating plant differs from land-based remediation. While there would certainly be site
testing and some ocean floor remediation, it makes more sense to compare floating platform decommissioning to the disposal costs incurred by large naval nuclear platforms. The most recent example is the *USS Enterprise*, which carried eight SMRs. Disposing of the *Enterprise*'s reactor compartment will cost roughly $750 M,\(^{(49)}\) which translates to less than $100 M per plant. This was a larger decommissioning effort than a commercial SMR barge would be, and if regulatory changes were introduced for SMR decommissioning funds, they would benefit the floating option. The U.S. Navy budgets approximately $120 M for the inactivation of a nuclear submarine,\(^{(47,49)}\) and has completed them for less, averaging $41 M (FY12) per ship for 11 submarines inactivated from 1988 to 1990.\(^{(49)}\) Costs for final disposition of floating variants of commercial reactors would likely be somewhat higher since naval plants are more compact and more readily buried, but overall decommissioning costs will still have more in common with a naval model and should be examined to see if there are benefits with respect to decommissioning that accrue to a marine model. Another factor in new site development is proximity to existing power infrastructure. The added complexity of a marine siting application will necessitate higher transmission costs. Cost factors from Siemens, Pacific Gas and Electric, the Edison Electric Institute, and MIT indicate that marine cabling costs could exceed $3 M per km, while land cabling is highly dependent on terrain, urban versus rural siting, and above versus below ground installation.\(^{(63)}\) With this in mind, costs for the floating application were approximated at a mean of $6 M per mile, while land rates were varied around $500 K per mile. Transmission distance was also varied for the two siting modes. Fig. 6 shows the CDFs of both options. As expected, there is a 0.98 probability that transmission costs for floating sites will be higher, with a median difference between floating and land sites of about $26 M. This cost is significant, and might conceivably become a factor in deciding between the two options, but it is dwarfed by the overnight cost.

A third potential cost overrun risk driver is the cost of the materials, since variability in commodity pricing affects proposed builds. To examine this, we compared the costs of concrete and steel in floating and land-based deployments. As shown in Fig. 7, model results indicate that material costs are consistently higher for the floating plant, given the greater weight and higher cost per ton of steel, with a median cost of $21 M compared to the land-based site’s median cost of <$5 M. Again, in absolute terms, the cost of materials is a minor factor in comparisons between the two options, and has less to do with acquiring raw materials than the on-time delivery of finished materials in a shipyard with high labor costs.

5.3. Accident Risks

5.3.1. Atmospheric Release Compensation and Remediation Risk

Nuclear reactors are required to maintain an EPZ.\(^6\) Analyzing EPZ risk requires a comprehensive site-specific evaluation, including extensive risk analyses that incorporate population density, demographic structure, weather patterns, seismic and other natural hazards, core load for the specific

\(^6\) For details on EPZs, see: http://www.nrc.gov/about-nrc/emerg-preparedness/about-emerg-preparedness/planning-zones.html.
Fig. 7. Cumulative distribution functions (a) comparing the material costs of the floating and land-based options, and (b) showing the difference between them. Concrete-intensive land-based plants dominate steel-intensive floating plants, given the greater cost of the latter; still, the cost of the materials is a very small part of the project total.

design, probabilistic risk assessment, and myriad other factors. Because our assessment assumes comparable plants both on and offshore, the safety features inherent to the chosen design would accrue to both options. A comprehensive risk assessment for the floating variant would likely favor better for seismic/tsunami risk, given the nature of the deployment method. The location in what is essentially an infinite heat sink would also weigh in favor of the floating option. Of course, risks for the onshore site will depend on location and nearby population and facilities. Risks for the offshore location include collision, flooding, stability impacts on flow characteristics, and emergency response availability. Because both are site specific, we do not include them in this first-order comparison.

Our model first provides a stylized order of magnitude estimate of the implications to EPZ risks as a plant’s distance from shoreline increases. Our results, shown in Fig. 8, suggest that the overall risk of compensation and remediation liability in the event of an accident is lower for the floating plant, given the reduced risk of plume exposure or ingestion. We assume a circular affected area of 10- or 50-mile diameter that begins at the coast and moves inland (land-based plant) or offshore (sea-based plant), modeled as a uniform distribution. A comparable population density distribution is used for the two modules, and a distribution of liability costs is developed using values from Three Mile Island (minimum),(54) Fukushima (mode),(55) and Chernobyl (maximum).56,57 As modeled, the fSMR platform would incur lower compensation and remediation costs 90% of the time in the event of an accident. The results are not quite as dramatic for the 50-mile ingestion pathway, but the floating site option would still have an ~60% probability of lower liability costs. The intent of the model is not to imply a deterministic exposure risk value for either siting method, but to point out the fact that the risk is more likely to be minimized in a floating plant due to its distance from population centers. In Fig. 9, we show an importance analysis of the factors involved in the analysis, and make the point just mentioned more obvious.

Clearly, we can postulate regional, weather, or site conditions where this is not true, which necessitates careful site-specific assessment of the consequences of NPP deployment, as required by regulation for any new plant. Additionally, we assume that remediation costs would be similar for all sites, but accidents are not uniformly severe, so impacts and costs will likely be lower for an fSMR if hull integrity is maintained and environmental release is minimized. The platform can be moved farther out to sea in the early stages of an accident as part of an emergency response plan, and this unique trait can mitigate the affected population’s exposure risk, though it might carry international legal ramifications. The option to move the platform would require further policy and liability assessment to ensure that the potential consequences have been considered—and emergency action plans are agreed upon—before first-of-a-kind deployment.

5.3.2. Marine Accident Consequence

The long-term consequences of environmental release from a reactor based on land have been well analyzed across a range of accident sizes,
Evaluating Floating SMRs

Fig. 8. Cumulative distribution functions (a) comparing the EPZ accident risk implications for the floating and land-based options, and (b) showing the difference between them. Our results suggest that the floating option has a >90% likelihood of reducing the implications of an accident, given the smaller affected population.

Fig. 9. From our importance analysis, it is clear that population density and the costs of remediation and compensation are the most consequential risk drivers for the land-based option. However, the ability to determine (or even adjust) distance from population centers affords the floating option greater flexibility in managing risk.

from Three Mile Island to Fukushima.\textsuperscript{(54–57)} Accident remediation is complex, time consuming, and expensive. While the probability of an accident at an SMR is very low, if significant releases do occur—as with Chernobyl and Fukushima—long-lived “no go” zones must be established, which carry with them environmental, health, safety, and economic impacts.\textsuperscript{(89)} Given Fukushima’s scale, some have even advocated delaying that affected region’s cleanup for 3–10 years to mitigate cost and exposure risk.\textsuperscript{(90)}

In addition to the literature on land-based accidents, there is a robust literature on past marine releases, including submarine sinkings, release in marine environments from U.K. and French reprocessing plants and, more recently, from the marine release at Fukushima.\textsuperscript{(89–101)} The overarching conclusion in this literature is that the long-term impact of marine release on marine biota and human food sources has been much lower than that found in large land-based releases. There remains uncertainty about the very long-term impacts on both aquatic and terrestrial biota from low-level radioactive contamination.

The most recent marine release example is Fukushima, where the magnitude of the total radionuclide release is still under review. Estimates have placed the marine release somewhere between 7 and 27 PBq for the key nuclide Cs-137\textsuperscript{(100)} (Note—some estimates are much lower.\textsuperscript{(97)} while some have placed it even higher.\textsuperscript{(100,101)}) I-131 releases were estimated at ~100–400 PBq. In the case of Fukushima,
the marine release was predominantly from seawater used to cool the damaged units and spent fuel pools.\(^{(97,99)}\) For land contamination, Cs-137 land deposition has been estimated at \(\sim 74\, \text{PBq} \) with I-131 at \(\sim 74\, \text{PBq} \)\(^{(97,100)}\). A 2015 report from the Japanese Atomic Energy Agency indicates that it will be years before the areas surrounding Fukushima will be decontaminated to the point of habitability.\(^{(99)}\) In contrast, though as much as 27 PBq of Cs-137 and 400 PBq of I-131 were released offshore, within two years the predominant number of biota samples taken offshore reflected contamination that was less than established limits. After four years, no fish samples contained concentrations of radionuclides above established guidelines (100 Bq/kg).\(^{(102)}\) It is true that seafood from the region has yet to be declared “safe for consumption,” but this reflects the dominance of politics and public perception in every postremediation decision that must be taken by the Japanese government.

Because our fSMR design assumes a smaller core load than that of Fukushima units 1–4, we incorporated a module in our model that scales the Fukushima findings (in percentage terms) to assess how a comparably sized release from an fSMR would compare. Note that for this type of significant release to occur, a multilevel failure of containment would have to precede the event or a nonfiltered release would be required as part of casualty mitigation efforts. We estimated the time at which the level of fish contamination would reach “less than” established limits, comparing it to the four years that were necessary for levels at Fukushima to drop below those limits. Of course, such an order of magnitude estimate only applies to this specific site since every potential fSMR site would have unique depth, current, and weather patterns, not to mention potentially far different biota composition. To model the release from an fSMR, we calculated a core load for a 225 MW\(_{\text{e}}\) plant, assuming fuel parameters comparable to a standard GW-scale LWR (light water reactor). The values we used are included in Table III. We assumed the highest estimate Cs-137 release of \(\sim 27\, \text{PBq} \) and I-131 release of \(\sim 100\, \text{PBq} \) and modeled the total release source term as a distribution from 80 to 130 PBq with modeled release as a percentage of the overall estimated core load of the four damaged reactors (attributing the majority of radioactivity content for the cores as Cs and I).\(^7\) This result is an overesti-

---

\(^7\) The two key radionuclides chosen for this first-order assessment (I-131 and Cs-137) were chosen because they have significant core
Evaluating Floating SMRs

Fig. 10. Our simulation of the impact of an accident with radionuclide release in a marine environment reflects nominally 2.7 years until contamination levels for fish in affected areas would sample at less than the established guidelines for radionuclide content. This estimate is specific only to Fukushima since the factors used reflect the unique currents and biota of that area. This is an improbable worst case for an fSMR but reflects an accident size that equates to the size of a Fukushima-level release for the smaller fSMR.

mate of core release (especially Cs-137), since some of the released radionuclides came from damaged spent fuel pools at the site.\(^{(97, 99)}\) We then calculated a decay rate for the contamination the fish population would be exposed to, using data published by the Japan Fisheries Agency.\(^{(102)}\) Were an fSMR to cause a release that is comparable in percentage terms to Fukushima, our results indicate that seafood would reach a contamination level “less than” established limits within ~2.7 years. The radionuclide inventory that would have to be released for this comparison to hold must, of course, be similar to Fukushima’s. Fig. 10 provides the CDF for the parameters modeled. Given the more advanced safety features of SMRs, ocean basing with abundant cooling water, and multilevel containment, we believe this order of magnitude estimate to be an improbably serious worst case.

Any environmental release has extremely negative consequences and, as has been well documented in the literature, the long-term impact of low-level radionuclides on the overall health of the local biosphere is not fully understood. As a result, any detailed siting analysis would need to attempt to minimize potential future impacts by placing the reactor outside of critical fishing grounds, just as land siting considers long-term risk to population centers and the food supply. Should an accident occur, it is critical to consider which parties would be liable for post-disaster cleanup, not to mention where a damaged fSMR could be taken and made safe. For any vendor nation, accepting custody of spent fuel is a challenging technical and political feat in itself. Taking custody of a damaged plant would pose even larger obstacles. This is an issue that arises in different forms under a BOOR model for either a land or sea case.

5.4. Water Opportunity Benefit

As we noted above, if options being considered for land sites in a host nation require use of a freshwater source for cooling, then a water opportunity benefit should be included in the cost/benefit comparison. Based on the size of our plant and commercial water rates drawn from arid regions, such as southern California, as well as more typical areas, such as the U.S. Pacific northwest and international values from Germany and Norway, model results indicate that there would be an almost $12 M per year “water opportunity benefit” when using ocean water for cooling instead of the freshwater sources that inland plants would exploit. Fig. 11 provides the CDF for this cost.

Water opportunity costs will vary based on plant location and size, but it is clear that the floating option avoids exploitation of scarce freshwater resources, a factor that could become more important as climate changes. In one recent assessment of SMR siting options, cooling water availability was deemed the most critical determinant of site suitability in the United States,\(^{(88)}\) and the same is probably true worldwide. Infrastructure planners concerned about conserving scarce water resources should evaluate

centration, have potential uptake in marine biota, have higher radioactivity levels (Bq), and have longer half-lives (I-133 and I-135 have higher radioactivity levels [Bq] but short half-lives).
Fig. 11. The annual water opportunity benefit associated with using ocean water for cooling, instead of the freshwater sources that an inland plant might utilize, is substantial. Cooling water availability is one of the main obstacles to siting large thermal generators, and given concerns over freshwater scarcity, it is wise to ascribe a value to this benefit for generators that do not rely on freshwater for cooling.

Incentives for new energy infrastructure that does not rely on freshwater withdrawal. Our finding suggests that a floating SMR could avoid the environmental impacts of inland energy infrastructure development. Not considered here are the floating plant’s potential secondary process applications, such as water desalination for arid regions or impacts from thermal pollution.

5.5. Implications of Floating SMRs on Nuclear Security

The proliferation risks associated with an fSMR that limits all handling of nuclear materials to a nuclear-capable state are lower for several reasons. First, it preempts the development of multiple national nuclear programs. Second, it eliminates the need for onsite refueling, reducing the risk of nuclear material being compromised. Third, it ensures robust material control and accounting practices are employed by restricting fuel handling to centralized, secure facilities under international supervision. In the same vein, it renders unnecessary the spent fuel pool, which is a substantial cost and risk driver on any site.

From a physical security perspective, an fSMR sited well offshore and away from sea lanes would enhance physical security by reducing the size of the defended area. Floating platform security would likely maintain a defense in depth approach, similar to that used by international navies. The platform and areas surrounding it—nominally to 1,000 yards—would be considered a “vital area.” This area would be protected in our model by a barrier fence, which we have incorporated into the cost structure for fSMR overnight costs. The area from 1,000 yards to approximately 5 nm would be an identification, interrogation, and engagement area. Finally, the distance to the horizon (nominally 12 nm) would be a surveillance area, incorporating radar and visual systems. Defensive forces would have a greater ability and time to assess incoming unknown contacts when compared to a land site, both due to a greater field of view and also, for typical surface and subsurface approach options, a much slower possible rate of approach than for a typical land assault. Approaching the fSMR site would be more challenging, and doing so covertly would require highly trained forces. Additionally, the subsea location of the core would render any attempt to cause a release at the site more difficult. Fuel handling materials would not be available onboard. Staffing the platform would be the responsibility of the contracting vendor, limiting both the need for human capital development in host countries and, with proper vetting, the risk of insider threat. However, this reduced insider threat risk would also apply to a BOOR land site.

There are several potential disadvantages, too. Among them is the potential for unauthorized movement or hijacking. The nature of the platform would make it challenging for any group to move the entire structure covertly before intervention from security forces. From a physical security standpoint, the offshore location will make host nation threat response
more challenging. This will, of course, be a function of the host nation and the breadth of security capabilities it can bring to bear. A full comparison of the vulnerability of a sea-based alternative to sabotage or terrorist attack will be an important consideration and will require security assessment for each host nation using ISO standards 28000 and 31000, which cover supply chain security and risk assessment. Risk mitigation requirements will also require individual analysis and deployment of fSMRs internationally. Importantly, it will also mandate updates to both the U.N. International Code for the Security of Ships and Port Facilities and the IMO International Ship and Port Facility Security Code. Finally, regulatory inspections may also be more challenging. Some floating designs have limited plant access and would challenge inspection protocols. Other factors, such as the risk of an insider threat, would remain regardless of deployment option.

6. CONCLUSIONS AND POLICY IMPLICATIONS

Despite having the substantial benefits of a nuclear fuel cycle that is managed by existing nuclear-capable states, increased scope for cost control, and more limited risk of exposure in the event of an accidental release of core inventory, floating NPPs would cost 1.5–2 times as much as equivalent, land-based sites if the former are built to stringent, quasi-U.S. military specifications for steel, welds, and quality assurance, assuming no significant cost overruns are incurred for the land-based plants. Nuclear technology vendors pursuing this option commercially must recognize that, through a combination of prudent risk avoidance and regulatory caution, they would likely have to contend with satisfying both nuclear and quasi-military design specifications, incurring a substantial cost premium over alternate generation options. While some customers might be willing to pay this premium, the prospects of deploying these plants at a rate sufficient to meet the developing world’s energy demand growth or mitigate climate change are probably not good. That said, our model does not quantify perhaps the most important benefit of the fSMR option, which is dramatically reducing the number of sites where special nuclear materials are stored, enhancing material control and accounting procedures, stretching the resources of organizations charged with oversight, and eliminating the risk of some material being compromised by political instability.

From our results, it is obvious that any vendor that chooses to offer fSMRs must invest substantial effort in defining standards for the commercial operation of this type of plant. Despite the potential safety and security benefits, there are uncalculated risks that the vendor will be required to address to perhaps multiple regulators’ satisfaction. The costs and benefits that are used in arguing against or for the concept are generally small in absolute terms. Ultimately, what will make this concept successful are its control of overnight cost, which could prove difficult, and its potential to radically alter nuclear power’s deployment paradigm by removing the custody of special nuclear materials from nations where institutional capacity is not yet developed enough to protect them and proliferation risks are an issue.

Construction of one floating nuclear platform is ongoing, and there is now real interest in the concept. The floating platform under construction is the Russian power barge—the Akademik Lomonosov. The barge is designed for use in remote areas that require electricity and process heat. It carries two SMR plants—using a variant of a Russian ice-breaker nuclear plant (KLT-40S)—each with a power output of ~35 MWe. While development to date has been confined to existing nuclear-capable states, some developing coastal nonnuclear nations that have expressed interest in nuclear power (Vietnam, Saudi Arabia, and Indonesia) may see an fSMR as a viable option to help address base-load power production needs while maintaining a low carbon footprint. To ensure the development of standards supporting this eventuality, near-term international regulatory assessment is needed to: (1) establish standards for fSMR development and deployment. The IAEA, International Maritime Organization, and the United Nations should establish guidelines for platform construction, evaluate accident liability regimes, and establish transportation, security, and proliferation protocols for vendor and host nations. These organizations have previously established guidelines for marine shipment of nuclear materials, which can be used to establish a baseline for construction safety. (2) Incorporate a floating siting option into ongoing international regulatory assessments of SMR and advanced reactor design licensing processes. If this technology is developed, we think it most unlikely that the effort will be based in the United States, both because of high costs, and because of the likely difficulties entailed in returning spent fuel. However, the United States is no longer the most active state in the commercial
development of nuclear power. Other states might see the development of an fSMR industry sufficiently attractive in geopolitical terms to accept the return of spent fuel, and perhaps even back a commercial undertaking with government funds.

ACKNOWLEDGMENTS

This work was supported by grant 12-101167-000-INP from the John D. and Catherine T. MacArthur Foundation. It benefited from interaction with the Carnegie Mellon Center for Climate and Energy Decision Making, which is supported by the U.S. National Science Foundation through cooperative agreement SES-094970 between the National Science Foundation and Carnegie Mellon University. Support for Michael Ford also came from the U.S. Department of Veterans Affairs and Carnegie Mellon University Yellow Ribbon Program.

REFERENCES

23. Steinbruner JD. Anticipating Climate Mitigation: The Role of Small Modular Nuclear Reactors (SMRs).
Evaluating Floating SMRs


60. Rothwell G, Glandon F. Electricity Generating Portfolios with Small Modular Reactors. Argonne, IL, USA: Nuclear Engineering Division, Argonne National Laboratory, May 2014.


SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher’s website:

Appendix A
Table A1. Plant siting criteria identified by the International Atomic Energy Agency

Appendix B
Analytica Model Structure
Figure B1: Analytica model main page.
Figure B2: Analytica model input/output page.
Figure B3: Analytica model fSMR page.
Figure B4: An influence diagram of the fSMR construction cost submodule.
Figure B5: An influence diagram of the fSMR transmission cost submodule.
Figure B6: An influence diagram of the fSMR decommissioning cost submodule.
Figure B7: The fSMR material cost submodule.
Figure B8: The fSMR EPZ submodule.
Figure B9: Assessing the area affected by a potential accidental release of radioactive material. The farther from shore the fSMR is, the smaller the population in the area covered by the fSMR’s emergency planning zone.
Figure B10: The fSMR compensated gross tonnage cost calculation submodule.
Figure B11: Analytica model land SMR site page.
Figure B12: An influence diagram of the land site SMR’s construction cost submodule.
Figure B13: An influence diagram of the land site SMR’s transmission submodule.
Figure B14: An influence diagram of the land site SMR’s decommissioning submodule.
Figure B15: An influence diagram of the land site SMR’s materials submodule.
Figure B16: The land site SMR’s EPZ submodule.
Figure B17: The land site SMR’s water opportunity benefit submodule.
Figure B18: fSMR marine accident release.