



Center for Climate and Energy Decision Making
5th Annual Meeting
***"Reducing GHG Emissions Through Low Carbon
Electricity Generation"***

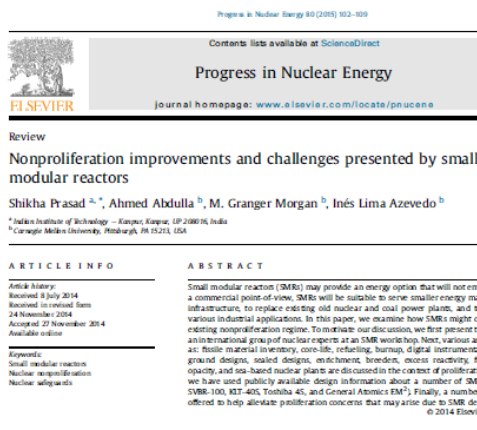
Floating Small Modular Reactors

21 May 2015
Michael J. Ford



Floating Small Modular Reactors - Context

- Prior work by Morgan, Azevedo, Abdulla and Prasad has examined potential and implications of SMR development



1. Introduction

In order to move towards a more sustainable, de-carbonized and reliable energy systems a portfolio of new energy technologies and strategies is needed. Among promising emerging technologies are small modular reactors (SMRs) (Abdulla et al., 2013). The International Atomic Energy Agency (IAEA) defines SMRs as nuclear reactors producing less than 300 MW of electricity (Small and Medium Sized R., 2013). SMRs might become an energy option which, like today's large reactors, will not emit greenhouse gases while having much lower initial total capital costs, and be more easily deployed (even in remote areas), standardized, and be safer (Abdulla et al., 2013; Liu and Fan, 2014). Such a technology could play a key role in a portfolio of generation technologies for a global reduction in carbon emissions. Since SMRs might be widely deployed if they become economically viable, it becomes imperative to examine the nonproliferation challenges they present and benefits they offer (O'Meara and Sargent, 2013).

This paper highlights and investigates how SMRs could improve and change the existing nonproliferation regime. This regime

involves a patchwork of international law, instruments, informal agreements, national pressure. The main pillars of this regime in proliferation Treaty (NPT), which bars all but nuclear weapons, and commits all states to Resolution 1540, which commits United States to counter nuclear terrorism by preventing getting into the hands of non-state actors. The IAEA is responsible for monitoring states' non-proliferation obligations are at right to monitor nuclear activity in member states and careful material control (International Atomic Energy Agency, 2011). number of nuclear sites, the total amount of nuclear material, or the geographic distribution greatly increase the amount of work under and also lead to an increase in the number of sites, or the possibility of errors in accounting of nuclear material in circulation. To investigate whether and to what extent

Expert assessments of the cost of light water small modular reactors

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Analysis and decision makers frequently want estimates of the cost of technologies that have yet to be developed or deployed. Small modular reactors (SMRs), which could become part of a portfolio of carbon-free energy sources, are one such technology. Existing estimates of likely SMR costs rely on problematic top-down approaches or bottom-up assessments that are proprietary. When done properly, expert elicitations can complement these approaches. We developed detailed technical descriptions of two SMR designs and then conducted elicitation interviews in which we obtained probabilistic judgments from 16 experts who are involved in, or have access to, engineering-economic assessments of SMR projects. Here, we report estimates of the overnight cost and construction duration for five reactor-deployment scenarios that involve 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 vary by more than a factor of 2.5. Expert judgments about likely SMR costs display an even wider range. Median estimates for a 45 megawatt-electric (MW_e) SMR range from \$4,000 to \$16,300/kW, and from \$3,200 to \$7,100/kW, for a 225-MW_e SMR. Sources of disagreement are highlighted, exposing the thought processes of experts involved with SMR design. There was consensus that SMRs could be built and brought online about 2 y faster than large reactors. Experts identify more affordable unit cost, factory fabrication, and shorter construction schedules as factors that may make light water SMRs economically viable.

nuclear power economics | technology assessment

Individuals, companies and other organizations, as well as governments, must make important decisions in the face of considerable uncertainty. Although 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 so 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 all the consequences their decisions will have.

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 multibillion 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 reach a downward-sloping learning curve (1), 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 nec-

Our brains are not well-equipped to make a value considerable uncertainty. As extensive it has now shown, we make such judgments using cognitive heuristics that, although they serve many day-to-day settings, can result in overcost that leads both lay people and experts astray to more complex and unusual problems (2, 3). Decision (8) offers a set of strategies for improving how tant decisions in the face of uncertainty.

In addressing such decisions, one should scientific, technical, and analytical evidence that ever, because such formal evidence often does not extent of what experts know, in addition to seeking advice, it is common in decision science to use formal systematic probabilistic judgments from intimately familiar with the current state of knowledge, such methods have been used to characterize climate science (12, 13), the impacts of climate (16), and the health impacts of environmental pollution (17). Of course, the same cognitive limitations that make it to make unaided decisions also arise when we provide probabilistic judgments (3). Too often, per advice, little or nothing is done to limit over reduce bias. Ubiquitous overconfidence (10) and from cognitive heuristics, such as availability adjustment (2, 19–21), cannot be completely eliminated. Well-designed expert elicitations can use a variety help improve the quality of expert judgments (9).

Expert elicitation about emerging energy deeply informed by careful technical analysis rare (22). Here, we report the results of applying to one such technology: integral light water small clear reactors (SMRs).

Why SMRs?

Morgan has argued that if aircraft were made an a time, in the way nuclear reactors were made in the U.S., “many travelers would find the acceptable and air travel would be much more and mechanics would have to be specially trained aircraft... many replacement parts would have made... [and] every time an aircraft experience engineers and managers would be unsure how lessons to other aircraft...” (23). There is no design giant-scale reactors in the way that Airbus A380s are built. However, by adopting one that could be mass produced in a factory quality control, and shipped to the field by road the nuclear industry might begin to look more industry. Because individual reactors would be

Nuclear Power for the Developing World

Small modular reactors may be attractive in many developing nations. Here is a blueprint for how to build them efficiently and ensure maximum safety.

In the United States and much of the developed world, nuclear power raises deep misgivings among many decisionmakers and ordinary people. Concerns about safety have been rekindled by the Fukushima Daiichi nuclear disaster in Japan. There are also long-standing worries over proliferation and spent fuel management. And the technology has proven expensive: its high capital costs, combined with restructured electricity markets that place heavy emphasis on short-term economic gains, cheap natural gas in the United States, and the absence of a serious commitment to greenhouse gas emissions reduction, make nuclear power uncompetitive in many markets. The four new reactors being built in the United States today are in states that have vertically integrated power companies, where public utility commissions can approve the addition of the cost to the rate base.

But nuclear power is not dead. Seventy nuclear reactors are under construction worldwide. Twenty-seven of those are in China, ten are in Russia, and six are in India. With few exceptions, these new reactors are of the large light water type that dominate today's commercial fleet, producing roughly 75% of the electricity in France, 30% in the United States, 18% in the United Kingdom, and 17% in Germany.

The same holds true when it comes to the development of new reactor designs. Some limited work continues in the United States, but efforts by its Department of Energy to rekindle interest among commercial players have been limited success. Germany, once a leader in advanced reactor designs, closed its reactor development laboratories some years ago, ending all such

research. Its labs now focus only on reactor safety for select advanced designs. However, China, India, Korea, and Russia continue to support vigorous development and demonstration programs.

As developed countries come to appreciate the magnitude of the effort needed to fully wean their energy systems off of carbon-emitting energy sources, there is a possibility that they will see a resurgence of support for nuclear power—presumably using safer and lower-cost technologies. In the meantime, the rest of the world will continue its present building boom and push on with the development of new designs.

Thinking small

Many proponents of nuclear power believe that the technology's problems can be solved through innovation. Some have held up a vision of small modular reactors (SMRs), capable of producing 5 megawatts to 300 megawatts of electricity that would be manufactured on a factory production line and then shipped to the field as a complete module to be installed on a pre-prepared site. Proponents argue that factory manufacturing would not just reduce costs (it could also result in dramatic improvements in quality and reliability. Moreover, if these SMRs could then be returned—still fully fueled—to secure facilities at the end of their core life, the risk of proliferation could be better managed.

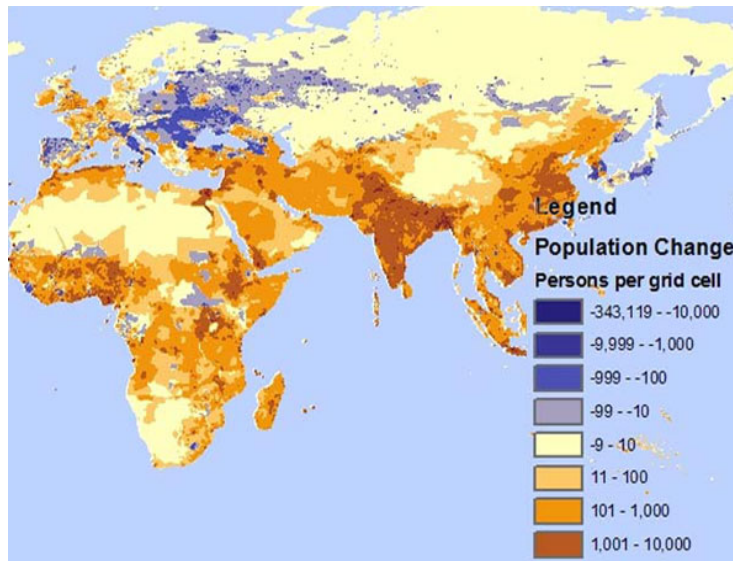
It is a lovely vision, but its realization lies decades in the future, if it is even possible. Estimates of the capital cost per megawatt of first-generation light water SMRs lie a factor of two or three above that of conventional reactors. Of course, since SMRs would be much smaller, the total cost would be much lower;

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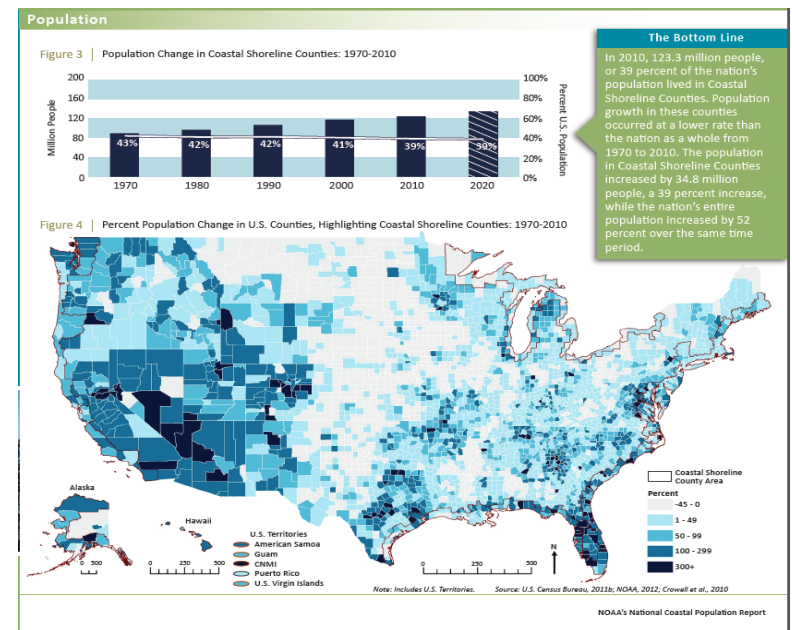


SMRs – A GHG Reduction Option?

- Population trends indicate continued coastal migration (McGranahan, et.al; NOAA; US Census...)
- Increased energy demand expected worldwide (IEA, EPA, EIA...)
- Climate change risks increasing for coastal communities (IPCC AR5; McGranahan, et.al)
- Existing coastal energy infrastructure increasingly at risk from flooding and extreme events (Heberger; Brown, et.al)
- Policy postulate: New generating capacity for coastal communities should be clean, safe, reliable, have low probability of proliferation AND should be adaptable to address increased energy demand, climate risk and GHG reduction goals
- Can Floating SMRs play a role?



<http://coastalcare.org/sections/inform/poor-coastal-development/>



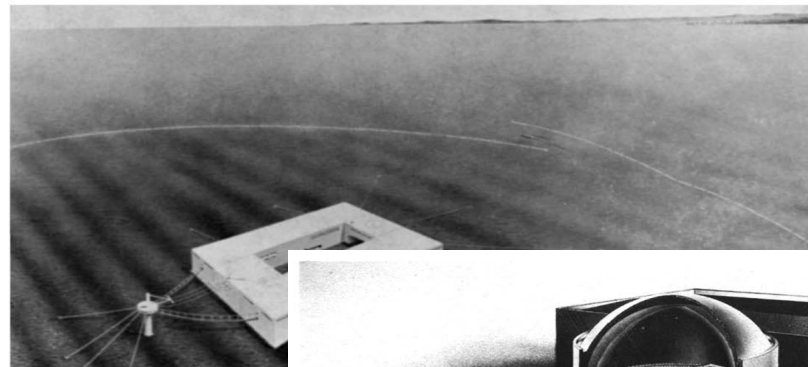
<http://stateofthecoast.noaa.gov/features/coastal-population-report.pdf>



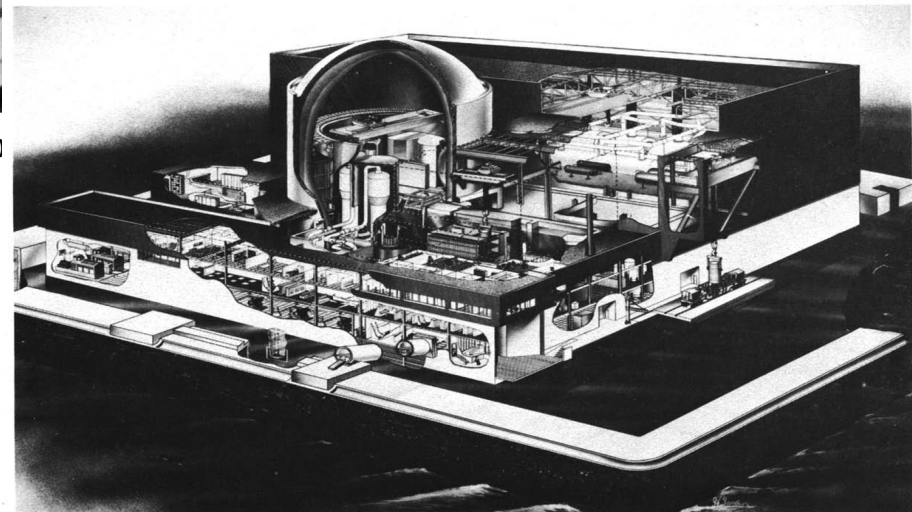
Floating SMRs – Not a new idea



<http://wikimapia.org>



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power plants.

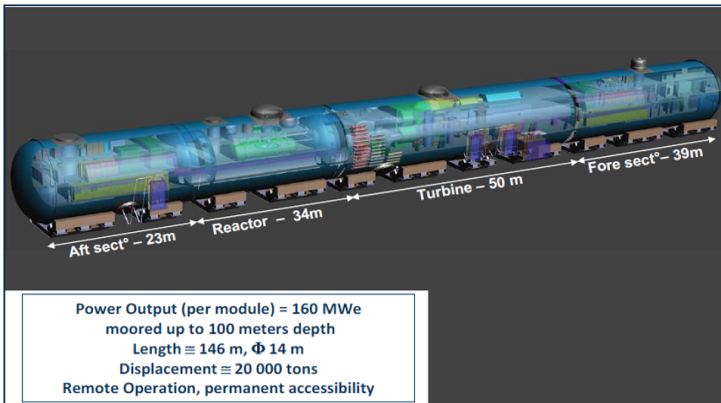


OFFSHORE NUCLEAR POWER PLANTS; Richard S. ORR and Clinton DOTSON



Floating SMRs – Current Concepts

Flexblue® : based on a Subsea Module



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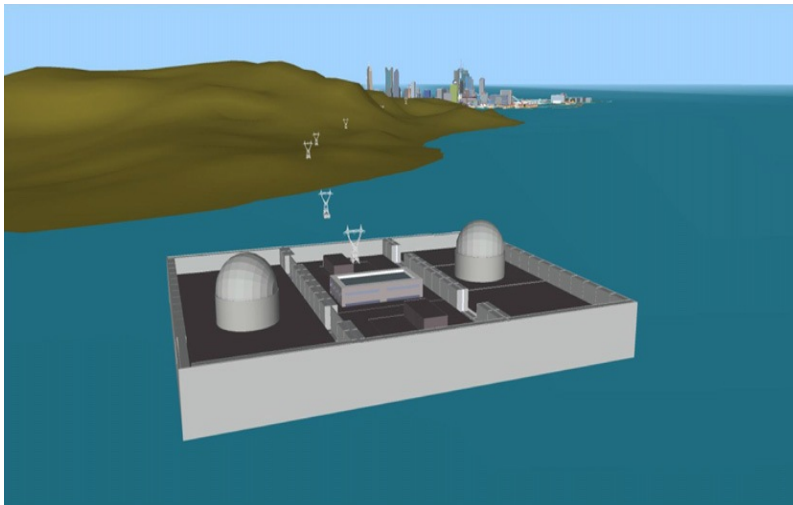
3 | July 2013 | 6th INPRO Dialogue Forum - Flexblue

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<http://newsoffice.mit.edu/2014/mit-offshore-floating-nuclear-plant-group-crowdsource-ideas-new-reactor-design>



Lee, K.H., Lee, K.H., Lee, P.S., Jeong, Y.H., Kim, J.K., 2011. A new concept of ocean nuclear power plant (ONPP). Nuclear Engineering and Design 254 (2013) 129–141



Photo source: <http://www.industrytap.com>



Floating SMRs – Examining Siting Issues

Initial Research Focus

IAEA Siting Criteria

Nuclear Power Plant Parameter Envelope

Health, Safety and Security Factors
Magnitude and Frequency of natural external events
Human Induced events
Radiological Impact
Security and Safeguard
Essential Supplies

Engineering and cost factors

Suitability of water for cooling
Suitability of existing electricity Infrastructure
Location of major load centers and selling price
Suitability of transport infrastructure
Technology considerations
Impact of existing facilities
Site development and construction costs
Multi-unit sites
Physical Security and Protection considerations
Stakeholder opinion
Regional regulatory and legal processes

Socio-economic factors

Future land use planning and sites ownership
Regional economy
Local Society
Landscape
Noise

Environmental Considerations

General eco-system characteristics
Aquatic ecology and marine impact
Terrestrial ecology
Freshwater Impact
Air Quality

IAEA Siting Criteria

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Technology considerations
Impact of existing facilities
Site development and construction costs
Multi-unit sites
Physical Security and Protection considerations
Stakeholder opinion
Regional regulatory and legal processes
Socio-economic factors

Future land use planning and sites ownership
Regional economy
Local Society
Landscape
Noise
Environmental Considerations
General eco-system characteristics
Aquatic ecology and marine impact
Terrestrial ecology
Freshwater Impact
Air Quality



Floating SMRs – study questions

- **What are the key economic factors for land based vs. floating SMR deployment?**
 - **Overnight cost and Cost-Overrun Potential**
 - **Material cost**
 - **Electrical transmission mode (submarine, underground, above ground)**
 - **Unique floating development, operations and maintenance costs (dry-docking, refueling, decommissioning)**
- **Is there a water withdrawal “opportunity benefit” for floating SMR deployment?**
- **How does a floating deployment method impact the Emergency Planning Zone?**



Floating SMRs – initial approach

- **Engineering Economic Model (@Risk, “R”, Top Rank)**
- **Initial Factors included in model:**
 - **Overnight Cost (Abdullah, Azevedo, Morgan Elicitation)**
 - **Cost Over-run Probability Factors (Shipbuilding, Nuclear Shipbuilding, Newbuild Nuclear)**
 - **Material Cost (steel/concrete)**
 - **Transmission Cost**
 - **Operations Cost (Manpower)**
 - **Dry-docking cost**
 - **Refueling Cost**
 - **Decommissioning Cost**
 - **Excursions**
 - **Inland freshwater “opportunity costs” (land based factor)**
 - **Depth of deployment (pierside to deep-water)**
- **TBD – Add’l Benefit, EPZ, Radiological Risk**



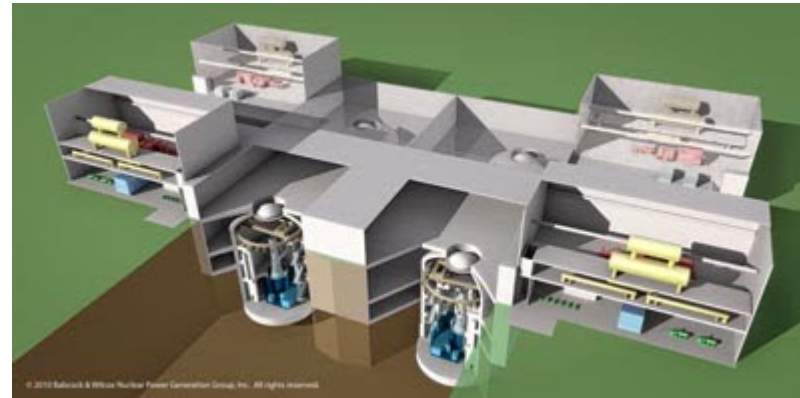
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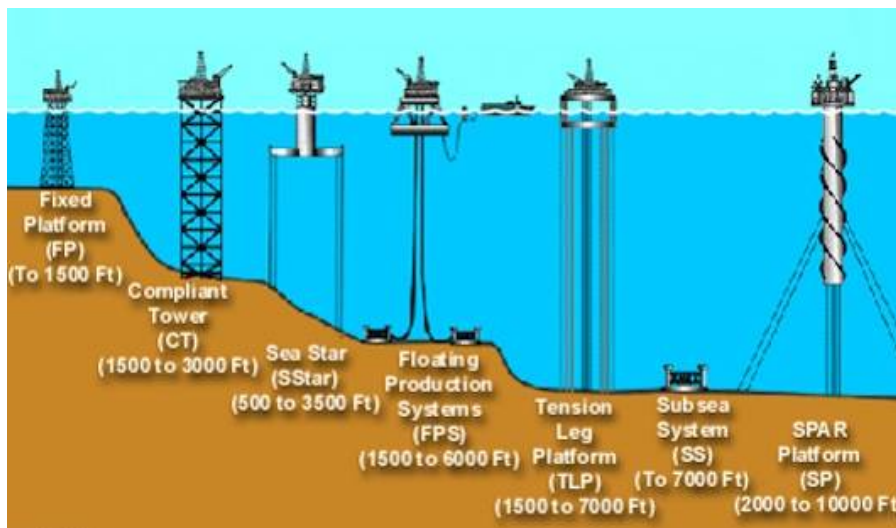
SMR Approaches Modeled

- Land Based:



B&W SMR – Photo accessed: http://alfin2300.blogspot.com/2010_07_01_archive.html

- Floating:

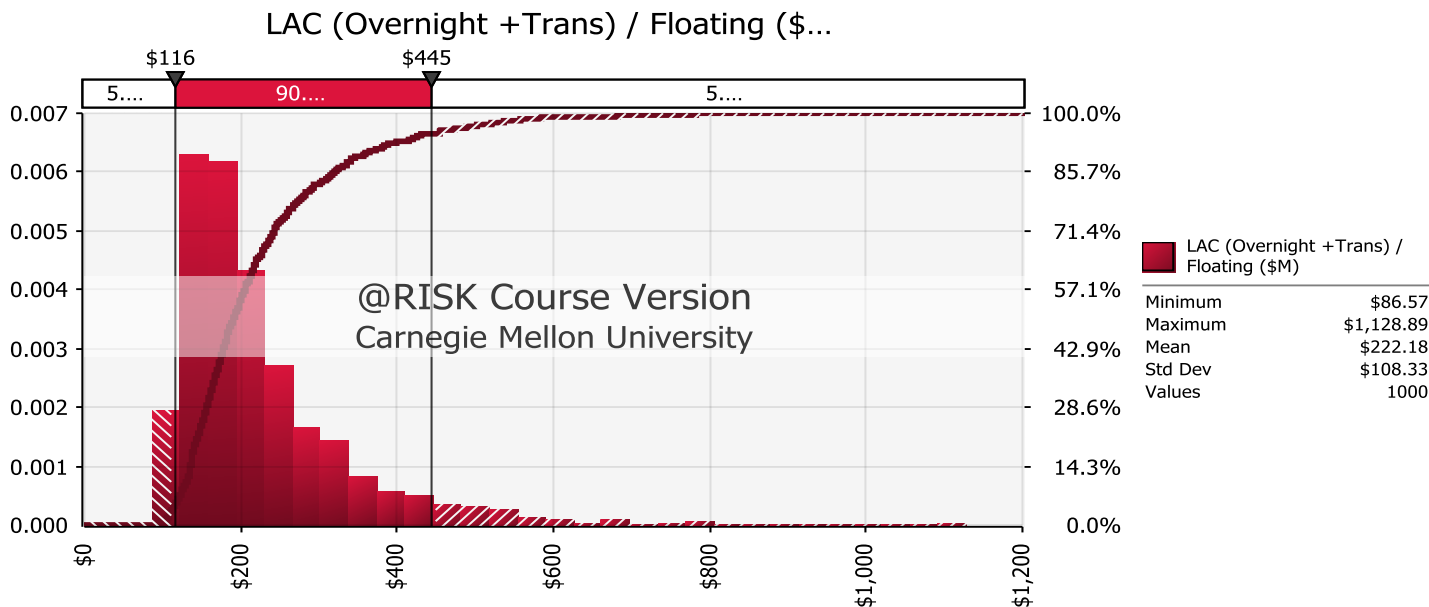


<http://www.mnn.com/earth-matters/energy/stories/types-of-offshore-oil-rigs>

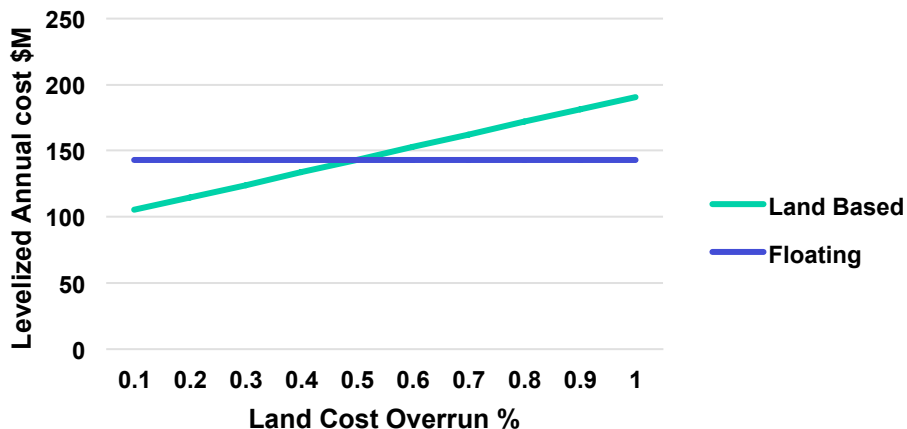
<http://www.bollingershipyards.com/news-resources/Bollinger-Re-delivers-Articulated-Tug-Barge-Unit-to-Bouchard>



Floating SMRs – (Very)Preliminary findings



Floating (20% overrun - Shallow) vs. Land Sited



- **Historical Mean U.S. Land Site Cost Overrun (GW Scale 1970s): ~200% (EIA)**
- **Current GW Scale: ~20-60% (2012 World Bank)**
- **Cost Overrun Range U.S. Nuclear Shipbuilding (NOAK) : 15-30% (GAO; Northrop Grumman)**



Floating SMRs – Research Support

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